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Physics Students' Epistemologies and Views about Knowing and Learning

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Abstract

Classrooms are complex environments in which curriculum, students, and teachers interact. In recent years a number of studies have investigated the effect of teachers' epistemologies on the classroom environment, yet little is known about students' epistemologies and how these interact with those of teachers. The purpose of this study was to document students' epistemologies and their concurrent views about knowing and learning. Using a written essay, short-answer responses to statements, a preferred classroom environment inventory, and interviews, students' views on scientific knowledge and their own knowing and learning were collected from 42 students in three sections of an introductory physics course. Our rather broad, qualitative inquiry provides a dynamic view of students' understanding of knowing and learning in high school physics. Our analyses reveal a spectrum of epistemological commitments commensurable with positions from objectivism to relativism, most of them with experientialist coloring. Even within individuals, these commitments could be at once commensurable and incommensurable with the same epistemological position. We also find rather significant inter- and intra-individual differences with respect to the consequences of a specific epistemological stance to learning, the learning strategies employed, and the learning environment preferred. Students' views on knowing and learning in physics are presented in the form of an emergent theory. The findings are discussed in terms of their application to classroom environments.

Rationale and Background

In recent years, many investigations have been designed to elucidate (a) teachers' beliefs and epistemological commitments and (b) the effect these beliefs have on classroom management (Clandinin, 1986; Tobin & Espinet, 1989; Tobin & Gallagher, 1987). On the other hand, little has been done to describe students' epistemological commitments and their effect on classroom learning. However, it seems reasonable to assume that students' views of knowing and learning will affect their stance toward the activities in the classroom. What happens in the classroom not only depends on how teachers conceptualize their roles, but also how students perceive and conceptualize their learning and the role of their teacher. "Their view of what

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learning is about is pieced together from their classroom experience and from the cues they detect in the culture and it is bound to have a significant effect on what happens to them in lessons" (Davis & Mason, 1989, p. 159).

Students' understanding of the nature of knowledge and the learning strategies that they consequently employ evolve throughout their time at school. The way the nature of knowledge is presented over the years of schooling is likely to affect students' understanding of it, and, consequently, how they relate to knowledge. If science is presented to students as a body of knowledge, proven facts, and absolute truths, then they will focus on memorizing facts and think that all knowledge can be ascertained through specific proof procedures embedded in the scientific method. If, on the other hand, students experience science as a continuous process of concept development, an interpretive effort to determine the meaning of data, and a process of negotiating these meanings among individuals, then students might focus on concepts and their variations. In addition, the actual content and the types of competencies sought within each subject contribute to student perceptions of that subject, as do achievement, competence, sense of efficacy, and learning strategies (Stodolsky, Salk, & Glaessner, 1991).

We understand the classroom as a dynamic conceptual ecology that involves the various social and cultural forces that students and teacher exemplify. In this ecology, the mind frames that students and teachers bring to the classroom interact in ways that are not altogether predictable. The possibility of meaningful learning in a science classroom rests on the assumption that students' *worldviews* are commensurable with those of science as it is taught. At the heart of it all, students and teachers must share some fundamental understanding of the culture of schooling for meaningful learning to occur. Without a shared understanding, teachers and students are literally in different worlds.

At present, most science teaching is based on an objectivist view of knowing and learning (Tobin, 1990a; Tobin & Gallagher, 1987). Here, objectivism subsumes all those theories of knowledge that hold that the truth value of propositions can be tested empirically in the natural world. Science provides us with a methodology, the scientific method, that allows us to transcend subjective limitations of individuals to test propositions and, in this way, to ascertain absolute truths. Traditional science teaching has focused on the direct transmission of these truths. To make this transmission effective, whole-class noninteractive and whole-class interactive activities are used by such teachers because they allow the coverage of much content. Thus, in many science classrooms, the norms are teacher explanation of concepts and procedures for calculating word problems to the whole class, followed by student seat work that emphasizes completion over comprehension. Small-group activities occur infrequently and are most often limited to data-collecting components of laboratory activities. Students, on the other hand, emphasize work completion, getting the right answers, and receiving satisfactory grades. When laboratory activities are used, they are recipe-like and emphasize the verification of known laws and law-like relationships. The goal of these activities is to ascertain the truths known about the state of nature. The outcomes of these activities are judged as matching or not matching the already determined truths in these matters (Tobin & Gallagher, 1987; Tobin, 1990b).

Constructivism has evolved as an alternative epistemology leading to a different view of learning. Generally, constructivists recognize a reality that exists independently of cognizing beings, but hold that direct access to this reality is forever elusive. People do construct personal knowledge about this world, and with it they construct the intellectual worlds that they inhabit (Goodman, 1978; von Glasersfeld, 1984). However, this knowledge can never be homomorphic with reality, but, in evolutionist terms, is adaptive. Knowledge "survives" when it is viable in the experiential world, but it is generally "abandoned" when individuals recognize that it cannot

describe their experience. Thus, in constructivism, the classical notion of truth is replaced by the notion of viability. This notion implies that there may exist alternative constructions, none of which can ever claim truth for itself.

Over the past two decades, objectivism has been subject to severe criticism by philosophers and historians of science, epistemologists, sociologists, and psychologists (Bruner, 1986; Feyerabend, 1978; Gergen, 1985; Goodman, 1978; Hesse, 1980; Knorr-Cetina, 1981; Kuhn, 1970; Rorty, 1979; Toulmin, 1982; von Glasersfeld, 1984). In addition, empirical work with college students made the claim that a constructivist position is a more mature form of knowing (Belenky, Clinchy, Goldberger, & Tarule, 1986; Perry, 1970). Consequently, many educators have accepted constructivism as a more appropriate set of beliefs to direct teaching and learning. However, to translate into classroom practice science educators' faith in a constructivist epistemology, teachers must recognize a need to change their views. Thus, science educators seek to help teachers in changing from worldviews that are commensurable with objectivism to ones that are commensurable with constructivism. Changing only teachers' views, however, may lead to discrepancies in the classroom ecology. We have to ask, "What happens if high school students face a classroom context that is based on a different epistemology?"

Few studies have investigated this interaction between the epistemological commitments of students and those of instructors or the curriculum. Schön (1987) used a case study from an architectural design studio to show how teaching and learning processes can go wrong. In this case study, the student felt that ideas were represented in drawings; the teacher felt that ideas arise out of the experimentation with various drawings. Because of their different views of what constituted knowledge, both student and teacher failed to construct shared meaning, and the teaching–learning process was disrupted. Belenky et al. (1986) discussed other examples of learning that were disrupted because of differing epistemological commitments between teachers and students.

We agree with Stodolsky et al. (1991) that students' motivational characteristics are important determinants of learning that may differ across the subject areas. However, students' views about the nature of knowing and the consequences they draw for learning seem to be even more important. If science is presented as consisting of facts with a vocabulary of historically and diachronically fixed meanings, then students' learning strategies should differ markedly from those that they exhibit in a subject where they learn science through interpretation of data and negotiation of meaning, and where they learn about the interpretive nature of science. Our research makes a distinctive contribution because it goes beyond a mere sampling of students' attitudes by investigating their epistemological commitments, their learning strategies, and their preferred learning environments. Our study also complements the research on teachers' epistemologies, beliefs, and attitudes by focusing on students' understanding of the nature of knowledge and the derived learning strategies. Before we can expect significant shifts in the epistemology of school culture, we must understand all three components of classroom culture: students, teachers, and the context of learning. Once the myths, metaphors, and conceptual framework of all of these components are known, they can serve as a powerful foundation for meaningful learning in a reconceptualized ecology of teaching and learning.

In this effort to complement the research on teachers' epistemologies and beliefs, we provide a broad and comprehensive survey of student views of knowing and learning science, which, to our knowledge, has not been done before on this scale. Particularly we were interested in finding the answers to three broad questions: "What are the students' epistemological beliefs?" "What are students' views regarding the nature of physics?" and "What are students' preferences for learning science?"

Design Issues

The present study made use of an interpretive research design based on principles of constructivist inquiry (Guba & Lincoln, 1989), constant comparative analysis, and grounded theory development (Strauss, 1987). Our intention was to develop working hypotheses in the form of assertions through an emergent design.

Participants and Classroom Context

The 42 students (4 from Grade 10; 38 from Grade 11) who participated in this study were enrolled in a junior-level physics course at a private, all-boys school in an urban area of central Canada. Because of its qualitative rather than quantitative treatment of physics, this course was very popular and enrolled about 60% of the students at Grade 11. Of the 42 students, only 23 took a more mathematical senior-level physics course. Although the students in this school traditionally are college and university bound, few of them (less than 5%) select pure sciences or mathematics as their major fields. Most of the students opt for careers in business, law, and general arts, whereas a small group select engineering studies. The special situation of the school provided for a distinct group of respondents, which is a goal of interpretive research. Such distinctiveness of group identity allows for replication or comparison with distinctly different groups and is the equivalent of experimental control in natural settings. To what extent was this group distinct? The chief characteristic that made this population different from students in a public school was gender and also the fact that all students were college or university bound. In terms of achievement, these students seem to be comparable to public high school students enrolling in physics. A third characteristic may have been in the nature of the physics course in which the students were enrolled, as described below.

All students had taken Grade 9 and Grade 10 general science courses, which consisted of one-third physics concepts. Most courses in this school are taught in a traditional, lecture-oriented fashion. Thus, the 41 students who were concurrently enrolled in a chemistry course experienced science as a subject in which "true" knowledge was disseminated by the teacher and the textbook. The teaching-learning environment in the physics course, however, was distinctly different. At the time of this research, the students had studied physics for 6 months in an open-inquiry environment. In this environment, practical and emancipatory interests were emphasized by the teacher, that is, students were in control of what to investigate, how to design the investigation, what materials to use, and what resources to consult.

At the beginning of each unit, students received a written outline of compulsory and suggested activities. There were four types of activities, such as experiments, reading and concept mapping, textbook problems, and essay assignments. Experiments made up the core of the activities around which the rest of the course revolved (70% of class time). Although the scheduled classroom time consisted of 9 periods per 2-week cycle, many students made use of the laboratory and its facilities during their spare periods, after school, in the evening, or during the weekend. The experimental work of the students was organized as open-inquiry. That is, the students were free to decide which phenomena to investigate (within the topics prescribed by the ministry of education), which research questions to frame, how to design the set-up, and how to collect the data.

At the beginning of each unit, students were introduced to the topic with a range of demonstrations. Through these demonstrations, students encountered new apparati, methodologies for collecting data, and data analytical tools such as mathematical and statistical software. Student questions that arose out of these demonstrations were flagged as potential foci

for student investigation. Materials were then made available for the students to familiarize themselves. Usually, students tinkered with the apparati and materials. Subsequently, they began their investigations, which were often based on phenomena they had encountered in their everyday lives. For example, students investigated the effect of wind friction, the friction of bodies falling in a liquid, or the effect of the thickness, length, and tension of a string on the frequency of the sound produced.

One or two periods per 2-week cycle were used for whole-class discussion, review, the sharing of experimental results, and concept-mapping activities. The work from the textbook was usually assigned as homework. For each unit, the students read the relevant chapters from the textbook and at least one other source, and they concept-mapped the key concepts. Each week, students selected and solved six to eight textbook problems from at least two sources. Students also prepared essays on special topics in physics not covered in their textbook. These included essays on "Knowing and Learning Physics" and "Objectivity in Science."

Data Sources and Data Collection

We used four primary data sources to allow for a triangulation of data. Our first data source consisted of five statements to which the students could respond with "agree," "disagree," or "other." We asked students to justify each of their answers in a 3- to 5-sentence statement. To assess students' epistemological commitments, we chose five statements that portrayed various aspects of the nature of scientific knowledge and the nature of its origin from either an objectivist or a constructivist position.

The second source consisted of an open-ended essay entitled "On the Nature of Knowing and Learning in Physics." The students submitted essays from 4 to 7 typewritten pages in length. To help the students in understanding the assignment, we gave the following instructions:

> In this essay, you should address the question of how we know and how we learn with a particular application to our subject, physics. You should ask yourself, *but not limit yourself to,* questions of the following nature.

Some of our suggested questions were: "How do I know physics?" "How do I learn physics?" "Is the knowledge you learn in the laboratory different from the one you learn out of the textbook?" "How does working in a group help me to learn physics?"

As a third data source, we administered the preferred form of the Constructivist Learning Environment Scale, designed to measure the extent to which students' preferred learning environments are consistent with a constructivist epistemology (Taylor & Fraser, 1991). The instrument consists of our subscales, each of which assesses an important aspect of a constructivist learning environment. The Autonomy scale measures the degree to which students want to exercise control over their learning activities. The Prior Knowledge scale measures students' inclination toward meaningful integration of knowledge. The Negotiation scale measures students' desire for opportunities to interact, negotiate meaning, and build consensus. The Student-Centeredness scale measures students' inclination toward learning as a process of creating and resolving personally problematic experiences. Taylor and Fraser reported alpha reliabilities between .69 and .85. for these subscales. The scales, typical items, and reliability estimates for this study are included in Table 1.

Interviews with 11 students constituted the fourth data source. We selected respondents on the basis of their potential to elucidate remaining questions. The selected students had demon-

Table 1
Results From the Constructivist Learning Environment Scale (CLES)

Scale	Typical item	α-Reliability (reported)	Mean[a] (N = 42)	Standard deviation
Negotiation	In this class, I would prefer to talk with other students about the most sensible way of solving problems (N)	.82 (.73)	3.78	0.55
Prior knowledge	In this class, I would prefer to think about interesting, real-life problems (N)	.54 (.69)	4.24	0.37
Autonomy	In this class, I would prefer that I decide how much time to spend on an activity (N)	.65 (.85)	3.62	0.46
Student centeredness	In this class, I would prefer the teacher to expect me to remember things I learned in past lessons (R)	.58 (.73)	2.72	0.41

[a] Items designated (N) are scored 1, 2, 3, 4, and 5, respectively for Never, Seldom, Sometimes, Often and Very Often. Items designated (R) are scored in reversed manner. A high mean, thus, corresponds to a more constructivist orientation.

strated during the regular class activities that they were both willing and capable of expressing their ideas and beliefs. Based on this criterion, we began interviewing a student from each of the opposing epistemologies and a student who held a view between the two extremes. Based on the information from the other data sources, we continued with students who we thought could answer some of the remaining questions. After we had interviewed a total of 11 students, we felt that additional information was largely redundant and we terminated the interview process (Lincoln & Guba, 1985). Although each interview was flexible, we aspired to (a) validate the student responses to the five statements by assessing their understanding of the questionnaire items; (b) validate the student responses in the essay format and on the questionnaire; (c) elicit students' reactions to discrepancies in their views; and (d) elicit any further beliefs that students held in respect to our area of interest. In the selection of interviewees we made sure that all ability groups were represented. Each 25 to 45-minute interview was transcribed so that it could be submitted to the same interpretive methods as written text.

We independently did a first analysis of all artifacts to produce some tentative categories. Then we collaboratively constructed, discussed, and refined our assertions. After identifying a new category of assertion we scanned all artifacts for confirming or disconfirming evidence. For example, from the analysis of the students' essays emerged a three-part conception of physics knowledge including mathematical, conceptual, and experiential aspects (see Assertion 5). We first re-read the students' essays where we found evidence for two *or* three aspects within each student. This seemed to disconfirm our initial assertion. However, through the interviews we asserted that even those students who had not mentioned a three-part division in their essays did so during the interview. Thus, we retained this assertion. On the other hand, on the basis of our information that students seemingly may hold views within both polar categories, we had to modify our first assertion, which put students into objectivist and constructivist categories. Hence, we now speak of views that are commensurate with the two polar perspectives without classifying individual students in any particular, ideal epistemology (Assertions 1 and 2).

Our analysis produced an inductively derived set of categories that will be presented with the results. The notions of reliability and validity are incommensurable with constructivist research and evaluation and are replaced by the parallel criteria of credibility and trustworthiness (Guba & Lincoln, 1989). Two major facets of our design contribute to its credibility and trustworthiness. First, we employed four sources to triangulate our data. During the interviews, we sought to resolve any contradictions constructed from the other three sources. Second, we brought two different perspectives to the study. As a teacher-researcher, one of us contributed an *emic* perspective to the data analysis. The other, a female university-based researcher, brought an outside, *etic* perspective to the data analysis. Because of our different status with respect to the school and the students, our study implicitly included those techniques Guba and Lincoln (1989) deem necessary for establishing credibility. Among these techniques are *prolonged engagement, persistent observation* (both due to the teacher-researcher's perspective), *peer debriefing* (the relation between teacher and university-based researcher), and *progressive subjectivity* (the joint construction emerging from the collaboration).

Constructions and Discussion

Our investigation was designed to determine three major dimensions of the physics students' views. First, we were interested in finding out more about students' epistemologies—that is, we wanted to elicit their views about the *nature of scientific knowledge*. It is to be expected that a person's view of the nature of scientific knowledge will interact with his or her specific views of what constitutes the knowledge of a particular subject such as physics. Thus, as our second dimension we sought to find out what students considered to be the *nature of physics*. These views in turn can be expected to interact with the *students' view of learning science*, our third dimension of interest in this study. We present our results concerning these three dimensions in the form of 4, 1, and 2 assertions, respectively.

The Nature of Scientific Knowledge

Our first instrument was designed to elicit students' views of the nature of scientific knowledge and the role of culture in the construction of this knowledge. A total of 36 students completed the instrument. Students' responses to the statements about scientific knowledge, science, and scientists are reported in Table 2. On first sight, the results seem to be discrepant. A majority of students indicated (a) that scientific knowledge is not artificial (61%), (b) that scientific knowledge more and more approximates truth (59%), and (c) that laws and theories exist independent of humans (69%). These positions are more commensurable with an objectivist view of nature and knowledge than with a constructivist position. The opposing views were held by 14%, 17%, and 25% of the students, respectively. These results are very much in agreement with results previously published. However, the majority of students also indicated that (a) science is based on presuppositions like art, religion and commerce (64%) and (b) the social environment will influence the content of knowledge that scientists propose (72%). Both of these results suggest that students hold a subjectivist view of the construction of scientific knowledge. The opposing views were held by 25% and 22% of the students, respectively.

To explore students' views further, we analyzed their justification for each of their answers, which we followed up during the interviews. A detailed analysis of the students' responses is presented in Table 3. We also classified individual categories as being commensurable with an objectivist (O) or a constructivist-relativist view (R). Those responses that could not easily be grouped with either view were classified as intermediate (I). Because we could ascertain the

Table 2
The Nature of Scientific Knowledge: Answer Frequencies

Question	Frequencies (N = 36)					
	Agree		Disagree		Other	
	N	%	N	%	N	%
1. Scientific knowledge is artificial and does not show nature as it really is (Gilbert, 1991).	5	14 5[a]	22	61 67[a]	9	25 28[a]
2. Scientific knowledge more and more approximates truth (Lakoff & Johnson, 1980).	21	59	6	17	9	25
3. Scientific laws and theories exist independent of human existence. Scientists merely discover them (Lakoff & Johnson, 1980).	25	69	9	25	2	6
4. Science, like art, religion, commerce, warfare, and even sleep, is based on presuppositions (Bateson, 1980).	23	64	9	25	4	11
5. The social environment of a scientist will not influence the content of the knowledge he or she proposes (Gilbert, 1991).	8	22 12[a]	26	72 60[a]	2	6 28[a]

[a] Percentages are Gilbert (1991) data for comparison.

roots of "other" responses in one of the two epistemological orientations, this in-depth analysis gave us an even clearer picture of the nature of students' ideas about scientific knowledge.

Assertion 1: When directly asked about the nature of scientific knowledge, its truth value, and its independence from human existence, a large number of students responded with views that are commensurate with an objectivist epistemology.

Table 3 shows that 27 to 29 (75–81%) of the students held views of the nature of scientific knowledge commensurable with objectivism. They believed that (a) science is not artificial but based on facts (18 students), (b) scientific knowledge is correct or false/artificial (6 students), and (c) science is the only correct vision of nature (4 students). These students also assigned truth value to scientific knowledge. Most of them (21) believed that it is a matter of time until all incorrect laws and theories are eliminated and until scientific knowledge is equivalent to the truth. For some (4), this process of eliminating false and incorrect scientific statements is unequal for different branches of science. Accordingly, scientific knowledge is only approximating truth, rather than being the truth. Students holding views commensurable with objectivism also believed that scientific laws and theories exist independently of humans, or that they are an expression of what nature really is. The following statement is representative of these students' views.

> Scientific knowledge is always progressive, as technologies allow man to see more clearly and to renew and improve old theories. Thus as techniques move forward, more and more is known and man moves closer and closer to understanding. Science is always a progressive art. . . . For this reason, barring catastrophe, scientific knowledge will always be approaching the ultimate and complete truth.

Table 3
The Nature of Scientific Knowledge: Content Analysis

Question	Answer categories[a]	Frequency
1. Scientific knowledge is artificial and does not show nature as it really is.	Science is not artificial but based on facts (O)	18
	Science consists both of artificial (false) and correct (true) knowledge (O)	6
	Science is the *only* correct vision of nature (O)	4
	Science is only a partial view of nature (I)	3
	There are multiple worldviews and science is just one of them, not more and not less correct (R)	5
2. Scientific knowledge more and more approximates truth.	It is only a matter of time until scientific knowledge is the truth (O)	21
	Science not only approximates but in fact is truth (O)	4
	Because of different rates of progress in its branches, science approximates truth in some areas but not in others (O)	4
	Truth is relative and absolute truth does not exist (R)	7
3. Scientific laws and theories exist independent of human existence. Scientists merely discover them.	Laws exist with nature whether there are humans observing nature or not (O)	22
	God created the universe with all its laws before man. Man only discovers God's code (O)	3
	Science is manmade, but reflects nature as it really is (O)	2
	Science is but one method of explanation for natural phenomena (R)	4
	Science is a purposeful human endeavor (R)	3
	Science is based on presumptions (R)	2
4. Science, like art, religion, commerce, warfare, and even sleep, is based on presuppositions.	Science is truth based on fact (O)	9
	Prior scientific knowledge affects future work (O)	8
	From presuppositions to truth (O)	4
	Sometimes (I)	4
	All human knowledge is based on *a priori* assumptions, or has unquestioned roots/origins (R)	11
5. The social environment of a scientist will not influence the content of the knowledge he or she proposes.	Science is based on numerical fact, which cannot be changed by the scientist's social environment (O)	5
	Rewards and recognition drive scientists to research in specific areas (O)	3
	Scientists are impartial and thus not influenced by their social environment (O)	3
	Equipment determines the areas a scientist researches and with it the knowledge he or she proposes (O)	3
	Depends on scientist. Some are influenced, others are not (I)	2
	There are cultural influences and institutions affecting the work of a scientist (R)	12

(*continued*)

Table 3 (*Continued*)

Question	Answer categories[a]	Frequency
	Language and perception are determined by the social environment and thus affect the results of scientific work (R)	5
	Zeitgeist determines what research is important and how it is to be interpreted (R)	3

[a] We assigned the students answers to three categories: objectivist (O), relativist (R), and intermediate (I).

A minority of students (19–25%) held views that were commensurable with a constructivist-relativist view of nature. They believed that science is only a partial view, or one of many views, of nature. As a consequence, absolute truth does not exist and is relative to human constructions. Some students argued that scientific laws and theories are constructed because humans want to understand nature. The laws and theories arise out of the purposeful endeavor to achieve this understanding. The integrated and differentiated views of these students are well expressed in the following statement:

> A scientist has a way of describing the universe's reasonably consistent patterns; so does an artist or a writer. Some say the scientist is the more accurate. Yet accuracy is a funny word to use when describing modes or stylistic algorithms that all by nature involve presumptions. Somewhere between them seems to lie the balance of human understanding.

Our results are similar to those reported by Gilbert (1991) in a study with college students that classified 67% and 5% as objectivist and relativist, respectively. With respect to the question of certainty of scientific knowledge, our results can be compared to data reported by Solomon (1991). In this study with 17-year-old British students, 62% believed in the certainty of scientific knowledge in the context of experiment and laboratory and only 22% accorded uncertainty to scientific knowledge. If we pool those responses, which agreed that scientific knowledge approximates truth with those which indicated that scientific knowledge is truth, then 69% of our students believed in the certainty and truth of scientific knowledge. In the light of the Perry (1970) and Belenky et al. (1986) schemes, that adherence to constructivist-relativist epistemology increases with age, the differences between our participants and the students in the two comparison studies are plausible.

We opened a very interesting and important window on students' views into the relationship of knowledge and nature. Some students indicated that laws and theories must have existed because "If it wasn't, things would have fallen before gravity was discovered and the sun wouldn't have worked because nuclear fusion hadn't been discovered. If this statement was false then humans would be the creator of the world as they assigned laws to it." Of course, these students confounded signifier and signified, a distinction made by Korzybski in the principle that "The map is not the territory and the name is not the thing named" (Bateson, 1980, p. 30). The students here did not distinguish between the Law of Gravitation, as formulated by Newton or any other scientist thereafter, and the natural phenomenon of falling objects.

We followed up students' views about the relationship between phenomena and their label. In our interviews, all 11 students made this distinction. They indicated that the actual mathematical formulations, the wordings and the pattern, were constructed by scientists. However,

the natural phenomena existed independently of our naming them, thus independently of human existence: "Apples fell before Newton came around and expressed the Law of Gravity in words and equations." We concur with others who indicate that student responses on questionnaires are inherently vague and can easily be misinterpreted by researchers (Lederman & O'Malley, 1990). This experience seems to make it mandatory to gather and clarify data through follow-up interviews.

Should we be surprised by these answers? Cleminson (1990) observed that the philosophical base of the curricula developed during the 1960s and 1970s was built on objectivism, which claims that scientific concepts could be learned simply by becoming good and unbiased observers. To date, science curricula have not kept abreast with contemporary notions in philosophy and history of science or sociology of scientific knowledge. Teachers—many of whom came through the programs of the 1960s and 1970s—also use, as intensive ethnographic classroom studies have shown, referents of actions with an implicit, objectivist epistemology. It can be expected that this epistemological climate provided by curricula and teachers would be an important determinant of the students' epistemological commitments (Tobin & Fraser, 1989; Tobin & Gallagher, 1987).

Assertion 2: A considerable number of students held views commensurable with a constructivist-relativist position when they talked about the presuppositions of, and social influence on, scientific knowledge.

Considerably fewer students than in the previous section held views commensurable with objectivism when questioned on whether science is based on presuppositions and whether scientists' social environments affect the content of knowledge they propose. The 21 students in this category believed that (a) science cannot be based on presuppositions because it is truth and based on facts (9 students), (b) prior scientific knowledge based on truth affects future work (8 students), or (c) science moves from presuppositions to truth because of its objective character (4 students). According to these students, science cannot be based on presuppositions because it is based on facts that can be observed, precisely and without any margin of error. Through experiments, scientists prove their laws and theories. Otherwise, science would be subjective, a contradiction in terms. The reason for this certainty of science is that "It uses proven facts as a basis for further knowledge, rather than basing it in 'self-evident truths' or preconceived notions." Fourteen students believed that the content of scientific knowledge itself is not influenced by the social environment. These students thought that (a) science is based on numerical fact, which cannot be changed by the scientist's social environment, (b) scientists are impartial and not influenced by their social environment, (c) rewards and recognition cause scientists to be productive in specific content areas, and (d) equipment might determine the experiments that scientists perform.

We thought that 11 students clearly held views commensurable with a constructivist-relativist position as they believed that scientific knowledge was based on *a priori* assumptions; or, they used a root metaphor according to which everything has to have some root or origin. In the words of one student, "Every concept in life must have had some sort of root or core to enable its belief." These presuppositions may be responsible for those aspects of our theories that do not exactly correspond to reality. In some cases, these presuppositions are the personal biases of the scientist, which, "Although they should not, do affect everything, including scientific findings."

Even more students (20) believed that societal influences shape the content of scientific knowledge. Students variously noted that (a) there are cultural influences and institutions which affect scientists' work (12 students), (b) language and perception are culture specific and thus affect scientific work (5 students), or (c) the *Zeitgeist,* such as the spirit reigning during the

Third Reich in Nazi Germany, determined what research is important and how it is to be interpreted (3 students). The views of these students are well represented in the following excerpt:

> The social environment includes anything outside the lab, such as home, church, and public. Therefore he/she [scientist] cannot avoid being influenced by people or the media. Thus, a scientist cannot be completely objective as religious, cultural, and other social influences sway his/her approach to problems and therefore alter the content of the accumulated knowledge.

In Gilbert's (1991) study, 12% of the students agreed that the social environment does not affect the content of new scientific knowledge, whereas between 20% and 30% in another Canadian study held the same beliefs (Aikenhead, 1987). If we pool those students in our study who clearly rejected the psychological effects of social interaction then our students (22%) are comparable to the other Canadian study.

Assertion 3: Students predominantly used metaphors with an implicit objectivist epistemology when they talked about learning science.

We found five metaphors related to the complex of knowledge and learning. These are, (a) knowledge as a material that can be transferred, (b) the mind as a container of knowledge, (c) knowledge as territory, (d) the brain as a muscle, and (e) knowledge and learning as constructed. The predominant metaphor was that of knowledge as a material that can be transferred or transported from one location to another, implying the objectivist conduit metaphor of learning (Lakoff & Johnson, 1980). The transfers could be from the head of the teacher to that of the student, from a book to the head of the student, or from the heads of students to the medium that they used to communicate. In all, we identified 33 different verbs that are entailed by the conduit metaphor. Accordingly, teachers *force-feed* students or *drill* knowledge into the brain of students. Students, on the other hand, *regurgitate* facts, learn until knowledge *sinks in,* or *take in* everything. The metaphor of knowledge as a material is related to that of the mind or brain as a container in which the knowledge is *stored, implanted, absorbed,* or *transferred by osmosis.* Students variously made reference to mind as a *pool of knowledge, store of knowledge, vat of knowledge,* or a *mindbook* to be filled with knowledge.

A second metaphor described mind in terms of a muscle that has to be *practiced,* which must be *exercised,* or which can be made to *work harder.* Knowledge was also described by the metaphor of territory or surface. Thus, students spoke of *boundaries of knowledge,* knowledge as a *territory to be conquered,* knowledge that can be *expanded,* or to *scratch the surface* of physics knowledge. Only a few descriptions of knowledge and learning were commensurable with a constructivist epistemology. Thus, students mentioned that *learning is interpretation;* that data and text do not have meaning by themselves, but meaning must be *loaned* to them; that ideas may be *formed* by an individual who *creates his own mindbook;* or that sense has to *evolve* out of discussions.

According to Lakoff and Johnson (1980), metaphors are not simply a matter of language; they are the very foundation of our conceptual system with which we think and act. Metaphors organize our experience and determine what we see, how we interact with other people and the world. Several studies showed the powerful influence of teachers' metaphors on their teaching styles and on the learning environment (Munby & Russell, 1990). When teachers change their metaphors on their own or through coaching, significant changes in the classroom environment can be observed. If these findings about the power of metaphors to structure our experience are

correct, then we may expect similar powerful effects of students' metaphors for knowledge and learning on their approaches to school.

Assertion 4: There was a considerable number of students who concurrently held views on the nature of scientific knowledge commensurable with objectivism and views on the influence of social relations on new scientific knowledge commensurable with a constructivist-relativist position.

We observed widely varying epistemological commitments among the students. A few students could be clearly identified as taking a constructivist-relativist position, whereas others clearly held views of the nature of knowledge more closely associated with an objectivist view. More important, though, was the fact that students concurrently held views commensurable with one position and with the other. A student who believed that scientific knowledge is absolute, that laws and theories exist independently of human observers, and scientists get closer and closer to the truth also believed that science is based on presuppositions, scientists' work is affected by the social environment, and science cannot be absolutely objective.

The students also used the metaphors of learning incommensurable with their other epistemological positions. We found that some students spoke about knowledge in constructivist terms, yet used metaphors for learning that derived from an objectivist epistemology (Roth & Roychoudhury, 1993). On the other hand, a student who indicated that he wrote his "own mindbook," a constructivist metaphor, held a view of knowledge incommensurable with the same position. Are the epistemological beliefs of students and adults generally coherent, and incoherent beliefs the exception? There seems to be evidence for the concurrent existence of beliefs and metaphors pertaining to different epistemologies in such a way that a clear identification of an individual with any one epistemology is impossible (K. G. Tobin, personal communication, June 23, 1991). Accordingly, situationally dependent referents determine the choice of a particular metaphor. This seems to suggest that it might be more appropriate to speak of epistemological positions only in specific contexts rather than as descriptors of an individual's views in general.

The existence of such dualities in students' worldviews has been recognized in the literature. Davis and Mason (1989) argue: "It seems that each person weaves a story in their head to account for their experiences, and these stories not only differ from person to person, but are often incompatible. Frequently they are even inconsistent within one person" (p. 163). During our interviews we challenged students to face the incommensurability of some of their own views, as we had constructed it, by using examples of contradictions in medical, legal, or environmental issues. Although all interviewees realized the incommensurability, none could resolve the issue during the interview. Some students argued that correct knowledge existed but experts did not have access to it at the point of their assessment. With time and more research, the experts could resolve these contradictions. These students clearly held views commensurable with objectivism. Others argued more explicitly that hidden variables affected the events under observation. By positing the right set of variables, we could know the outcome of experiments. This form of resolution to philosophical and epistemological problems of a theory, namely the search for hidden variables, is not new to science and has been at the center of an ongoing controversy in quantum mechanics. However, we would not expect students to resolve the incommensurabilities of their views on different issues within the duration of an interview. It is more likely that such resolutions and changes in epistemological commitments will require long exposure to a conceptual ecology of conflicting ideas in a classroom supportive of such changes.

The Nature of Physics

Assertion 5: The students view physics knowledge as consisting of three aspects, a mathematical and a conceptual, both of which are transmitted by textbooks, and an experiential rooted in everyday and laboratory experience.

The students' views on the nature of physics could be grouped along two dimensions, a cultural and an individual. Accordingly, most knowledge about physics is cultural and passed on to students through textbook and lectures. This culturally mediated physics knowledge consists of *mathematical* and *conceptual* aspects. The second dimension of physics knowledge is a personal one. This type of knowledge is constructed in *everyday* life and during laboratory activities. A summary of the categories derived from the students' essays and interviews is presented in Table 4.

Mathematical Aspects. Although all students referred to the mathematical aspects of physics, only 27 (68%) did so explicitly. Some considered the mathematical aspects to be obstacles to their effort to understand. These students mentioned mathematics with a tone of disgust, pointing to their own weaknesses, which prevented their doing well on the mathematical part of physics. Fourteen of the 27 students who made explicit reference to the mathematical side of physics explained that they didn't like this aspect of the subject. Remarks such as "Physics is almost too mathematical, [numbers] lose their meaning and many things are not explained in [numbers]" were very common among these students. For eight students, the mathematical aspects of physics were very positive, helpful, or time and energy saving. Among these students, a majority also made connections between mathematics and physics. They gained a mathematical understanding through the practical aspects of the mathematics in physics. To them, formulae acted as summaries of ideas. They could (a) understand the concepts behind these equations, (b) recognize the connections between various parts of the physics curriculum, and (c) see in these formulae a live application of mathematics. Students in this group also indicated that once they understood the link between mathematical and conceptual aspects, they could derive any other equation they needed. Five students explicitly indicated that by working through the lab, discovering relationships between variables, and processing the data in other forms they learn the equations they needed to know. Because one objective of the course was for students inductively to arrive at the equations they used for solving textbook problems, it is surprising that more students were not at ease with the mathematics. A possible explanation may lie in the abstraction involved that leads from observation to data collection and transformation to the actual equation derived from the experiment.

Four students stressed the philosophical aspects of mathematics in physics. For these students, physics is truth because it is based on mathematics, "the queen of all sciences," which not only expresses truth, but is truth. Accordingly, the order that scientists discover in the universe must be due to the underlying mathematics. The link with mathematics reveals that there is "a sort of philosophy embodying the Earth and the rules which govern it." In the answers to these students one can sense the same kind of awe that inspired the Greeks to link the harmonies of music, the mathematical description of the sounds from stringed instruments, and the periodicity of celestial phenomena.

Conceptual Aspects. As with the mathematical aspects, students also expressed reservations about the conceptual aspects of the course, particularly that part of the course during which they worked with the textbook. Students felt in part that these "concepts from the textbook had

Table 4
Students' Views of the Nature of Physics and Learning Science

Answer categories	Answer frequency (N = 40)	(%)
The Nature of Physics		
Physics as application of mathematics		
Physics has a lot to do with mathematics.	27	68
I don't like the mathematical part of physics	14	35
The mathematical equations in physics are useful	8	20
Physics is truth because it is built on mathematics	4	10
The lab helps me learn the mathematical equations.	5	13
Physics as conceptual framework		
Textbook knowledge is identical to lab knowledge	8	20
Physics and everyday experience		
Physics is everywhere around us	10	25
Lab knowledge is useful in everyday life	22	55
Learning Science		
Learning in the laboratory		
In the lab I figure out things for myself	27	68
Lab knowledge is the same as textbook knowledge	8	20
In the lab I learn to interpret, and learn through interpretation	24	60
Learning in groups		
Working in groups helps learning in the lab	36	90
I don't like working in groups	4	10
The group helps in interpreting data	24	60
I learn by teaching other students	6	15
When you work in a group you learn more from your peers	18	45
Three or four are better than doing the experiment by yourself	17	43
Getting work done is more important than immediate understanding	4	10
Learning to team-work prepares you for life	7	18

to be memorized and regurgitated." In general, these feelings toward the conceptual aspect of physics were generated by a sense that "concepts are logical [and] very different from everyday thinking." As we will see later, the relationship of learning physics with everyday experience was very important to the students, but they did not experience this relationship when they worked with the textbook. Because of it, students deemed the conceptual framework equally *dry, narrow,* and *stale*. Most importantly, they felt that textbook knowledge was secondhand knowledge, ofttimes of very limited scope, which did not allow "step by step, progressive learning to higher comprehension." As a consequence of these attitudes, students felt that they had to memorize concepts, and for that part of the course would prefer a *force-feeding* or *spoon-feeding* method. Eight students made explicit reference to the fact that textbook knowledge and the knowledge they gained from the laboratory work was "identical in its skeletal form but when the realism comes into it then the labs provide more answers than those in the textbook" or they "remember[ed] what [they] learned through the lab better than by reading it out of [their] textbook."

Physics and Everyday Experience. While all students made implicit reference to physics knowledge as having an experiential component, ten students made explicit reference to the effect of physics on their lives. To these students, physics occurs everywhere and is a fundamen-

tal part of everyday life on earth. As children we become intuitively aware of the laws of physics, because we play with bricks and balls, build toy houses, and learn physics "under the guise of household science before we ever come to school." In this way, we are already intuitively aware of physics, which makes it "reside at the edge of [our] tongue."

Experience was recognized by many students as "the greatest teacher of all." Experience increases that knowledge, which is applicable to real life, while "raw knowledge" from the textbook only leads to "regurgitable facts." With the applicability to real life, experience also imparts a sense of comprehension, which creates a better foundation for further learning. To expand this experiential base, physics has to be learned and taught in the laboratory. The link that learning in the laboratory affords with everyday life is bidirectional: knowledge constructed in the laboratory can be applied to real life, whereas everyday experience helps with learning in the laboratory.

Twenty-two students (55%) made explicit reference to the usefulness of knowledge gained in the laboratory to everyday life (Table 4). This knowledge is practical and helps students with the mechanics and applications in the real world. For example, a group of students was interested in the physics of music; through a number of self-designed experiments, they explored the effect of tension, thickness, and length of a string on the frequency of the sound produced by this string. Subsequently, they expanded their investigation into resonance phenomena:

> When we do many labs . . . we are learning how to apply the various ideas to the world around us, such as knowing why some seats are better than others in a concert hall because of resonance. . . . When my lab group studied resonance I think I can honestly say that we were all astonished at how much the volume of the sound increased simply by creating the proper length standing wave. . . . We found the increase quite dramatic.

These students felt that what they studied in the laboratory not only helped them learn the material but also established a network of knowledge that connected various parts of their lives, in and out of school. They felt that this knowledge, in contrast to many things they had to learn at school, was actually usable, meaningful, and worthwhile to be learned. Because of this complex web of connections between the learning in the laboratory and learning in everyday life, "physics is interwoven with our lives to a great extent that its ideas and connections remain in our minds like the alphabet."

Students' Views of Learning Science

In our investigations about how students view science learning (particularly physics) we constructed two major dimensions from the data. Thus, students spoke extensively about their learning experience in the laboratory and about learning in groups.

Assertion 6: The students considered laboratory work as an important aspect of learning science. It gave them a great degree of autonomy in learning and fulfilled their needs for a meaningful integration of knowledge.

The students wrote and spoke extensively about their learning in the laboratory. The following quote exhibits all the components of learning that we identified from our data:

> Students must experiment to fully master a certain notion. . . . Since their brain is involved in the process of interpreting the data and relating it to the notion in question, the knowledge afterwards resides longer and is more fully comprehended. Knowledge from the lab is intrinsic to the learning process.

We can find the notion that (a) knowledge is constructed individually ("intrinsic"), (b) laboratory work leads to meaningful learning ("more fully comprehended"), and (c) individual learning is achieved through interpretation of data and other sensory information.

Twenty-seven students (68%) referred to the individualistic nature of learning in the laboratory (Table 4). They felt that in the laboratory they became participants in generating knowledge. This knowledge served them in two ways. For one, it can expand, elucidate, and make meaningful what they learned from their textbooks and "fill the holes which are left from reading the textbook." On the other hand, this knowledge may also become the framework to which students connect textbook knowledge. Constructing knowledge on their own or teaching themselves and peers fills students with pride, affecting their attitude toward the subject and toward further learning. Students realized that they could "figure things out for [them]selves," "make theories and conclusions that [they] would not have realized," or "prove for [them]selves theories and facts." The feeling of personal involvement in constructing knowledge also gave students greater confidence in their abilities for learning in school because, "[In the lab] I have learned to organize and interpret results; this has helped me to gain knowledge, understanding, and confidence." The importance of autonomy to students was confirmed by the results on the Constructivist Learning Environment Scale (CLES, Table 1). The high score on the autonomy scale ($M = 3.62$, $SD = 0.46$) can be associated with (a) students' preference for the laboratory where they conducted independent, open-inquiry investigations and (b) their negative attitudes toward teacher and textbook-controlled learning. On the other hand, the result on the student-centeredness scale—that is, the extent to which they experience learning as a personally problematic experience—showed a different trend. The low mean score ($M = 2.72$, $SD = 0.41$) seems to indicate that students want teacher guidance as to the "correct way of doing things." Our analysis of individual items within this scale revealed a particularly low mean score ($M = 1.79$, $SD = 0.81$) for the question "In this class I would prefer the teacher to show the correct method for solving problems." There are two, not necessarily exclusive, interpretations for these results. First, as most of the students in this course are college bound, they are very concerned with the grades they receive. In this school, though not in their physics course, students were rewarded for conforming to a teacher's view—the correct view. A second possible interpretation is with reference to the students' epistemology. When students subscribe to a view of knowledge commensurable with objectivism, they seek the right answer because it is truth or approximates truth.

Students indicated that by doing the inquiry laboratories they developed a greater understanding and more meaningful knowledge. Although eight students said that the knowledge they constructed from writing the labs is similar to that which they could have learned from the book, they realized that the difference lay in deeper understanding and longer retention of what they had learned. Learning itself was facilitated through the engagement in activities with concrete objects. Thus, students discovered not only the conceptual but also the procedural aspects of doing and knowing physics.

Twenty-four students indicated explicitly that learning to interpret and learning through interpretation had become an important part of the course. They realized that the laboratory activities provided them only with raw data, which do not have meaning in themselves. This raw information must first be examined and interpreted before the results can become meaningful and before one can "evolve sense out of the results obtained." The process of interpretation in which the students were actively involved allowed them to generate their own knowledge rather than to be passive receivers of bodies of knowledge from books and teacher. In this way, the principles of physics were meaningful because they were generated on the basis of students' prior knowledge. The importance of prior knowledge to student learning was confirmed by the

results from the CLES (Table 1): prior knowledge had the highest of all scale means ($M = 4.24$, $SD = 0.37$). These students also indicated that the reevaluation of one's own ideas during the process of interpreting new information leads to further learning. Because it was based on their prior knowledge, students considered "Interpretation [as] the actual learning process which varies from person to person." To ascertain that this personal knowledge can be generalized, students emphasized the importance of group work through which meanings could be negotiated.

Assertion 7: The students experienced many benefits that arose from learning in groups such as synergistically arriving at better ideas, learning to negotiate meaning, learning to teach each other, efficiently completing tasks, and learning to team-work.

An important part of students' comments was devoted to learning physics in groups. We identified five major dimensions in their conceptualizations of group work. First, joining their efforts helped students to scaffold each other to new competencies. These new skills arose synergistically from the interaction of all team members. Second, because the inductive work in the laboratory required intensive interpretation, the coordination of different points of view helped team members to understand better the significance of the experiments and the results. Third, during collaboration, students were often required to assist others, which helped them in elaborating their own understanding. Fourth, working in groups was an important component in fast and efficient task completion. Finally, students felt that team-working in school prepared them for real life where cooperative skills are increasingly important. Each of these dimensions will be discussed under the headings of *synergism, negotiating meaning, reciprocal teaching, task completion,* and *learning to team-work.*

Synergism. Of the 42 students in the study, only four students (10%) indicated that they did not like to work in groups, nor did they like to learn in a laboratory setting (Table 4). They preferred to attend in a lecture-style classroom, be told what to study, and be tested exactly on what they were told. The students who liked collaborative learning indicated that there were many advantages to learning in groups. For one, in groups they could share in the whole task such that each group member not only takes on one part, but also serves as a critic for other students. They indicated that group work encourages students to work together and to merge all of their ideas into one, which gave a "better knowledge output" because three or four minds working together are undoubtedly better than one. One student wrote, "My strengths are in the organizational branch, another partner enjoys performing technical tasks, and the other tends to be involved in the thought processes, although we all contribute to the final claims." Recent research confirms these students' perceptions, indicating that groups of students who serve as resources for one another in exploring new domains can achieve levels of performance that individual members could not achieve (Rogoff, 1990). Supporting evidence for such scaffolding came also from an investigation that had studied computer clubs. This study revealed that nonexperts bootstrapped their performance to expert levels by pooling their individual knowledge about computers and constructing synergistically new knowledge frameworks (Collins, Brown, & Newman, 1989).

When our students worked in the laboratory, they achieved these scaffolding and synergistic effects as they tried to come to grips with differing interpretations and points of view. Such effects have been described in the literature (Brown & Palincsar, 1989; Collins et al., 1989; Rogoff, 1990), but it is remarkable that the present description emerged from the students' responses. More importantly, scaffolding and synergism are salient features of collaborative learning in cognitive apprenticeship, a central metaphor for the teacher-researcher in this study to conceptualize his or her role in the classroom (Brown, Collins, & Duguid, 1989).

Negotiating Meaning. Different points of view also led to new understanding. Sometimes students discuss ideas to find out which are the best ones. At other times, a fresh idea helps improve on an old idea, which then can grow into a new and better idea. Different group members may have different ideas or different interpretations of a student's own expression. However, through the reaction of peers, students could learn more about their own ideas as they are reflected upon by the group. Trying to understand another person leads to a better understanding of the topic because it lets one take a different view of one's own position. The negotiation subscale of the CLES—which measures students' desire for opportunities to interact, negotiate meaning, and build consensus (Table 1)—confirmed the importance of interaction to students and had the second highest scale score (M = 3.78, SD = 0.55). One student summarized the ideas of many of his classmates:

> The group discussions add much to all of our knowledges, as each one of us have [*sic*] a slightly different perception, and view of the results we obtained through the lab. This leads to slight differences in opinion which are easily resolved, and all members of the group gain from this experience. Thus I get a new perspective on physics when working in a group that I would have overlooked if I was working alone, and this new perspective adds to my knowledge and understanding of it.

Students expressed views similar to research findings on collaborative work among peers. This research indicates that social interactive methods are promising because they engage students in discussions during which they have to explain, elaborate, and defend their own positions. Through this process, they evaluate and integrate their own knowledge in new ways, thereby constructing new and more powerful ways of knowing (Brown, 1988; Cobb, Wood, & Yackel, 1991). Brown argued that as students try to convince each other, they have to verbalize and make explicit their own understanding, which is often only implicit. In the process, they have to examine their understanding in detail, which leads to the identification of incongruities and inadequacies.

Reciprocal Teaching. Both listening to peers or teaching them helps students to learn and understand physics. Six students indicated that they prepared others for examinations, rather than studying the material by themselves. They felt the best way to learn is to teach others. Many successful teachers have made such remarks: they truly began to understand after they have taught a specific topic for a number of years. The students also found that the questions that their peers asked them were among the more difficult ones to answer, much tougher than those they could find in the textbook. Reciprocal teaching offers advantages for all students involved (Brown & Palincsar, 1989). Although the students here did not collaborate in an environment as strictly controlled as those in the studies reported by Brown and Palincsar, some of its key features were preserved in the present context. Because group members tried to achieve consensus regarding meaning and importance, this setting was ideal for the emergent skills of individuals. As they constructed new knowledge in the group, they did not have to take individual responsibility for the whole task, but only for part of it. However, help was always close because "If someone in the group [didn't] understand something, he [could] ask someone else in the group to help him." Because the discourse remained at their own level, "It [was] easier to understand when it [was] explained to you by another student. So when you work in a group, you automatically learn more." This view is in agreement with research on collaborative learning, which noted that, because only peers can exchange interactional roles with the same intellectual content, reciprocal teaching situations allow students to both give and follow directions or to ask and answer questions (Forman & Cazden, 1985).

Task Completion. An important aspect of group work is task completion, which for four students was more important than comprehension (Table 4). When students collaborated, they felt that work could be done three or four times faster. This was of particular importance in the present environment where students designed experiments on their own, with little guidance from preestablished procedures or prepared laboratory equipment. In such an environment it is crucial that there is "A group you can ask . . . but if you are alone you will waste time trying to figure out insignificant details of your experiment." Thus, working in a group "gets the job done on time." According to other students, the additional resources of a group allowed them to design more complex experiments because they could share and thus still end up with reduced workloads. They indicated that more complex experiments were more interesting and gave rise to more learning in a shorter time. Any problems that arose during the work could be resolved much more quickly than if individuals had to solve them on their own. Besides, as groups had more resources than individuals, tasks could be completed more independently from the teacher, and results could be achieved without unduly wasting time waiting for the teacher to help.

Learning to Team-work. Teamwork in the physics classroom prepares students for life. In today's working world, teamwork has become increasingly important. "In the working world, all projects are with other people. Therefore, knowledge of working in groups is fundamental for succeeding in one's occupation." Students felt that learning to work in a team taught them how to build working relationships and how to develop skills for planning and decision making in group situations. Thus, students recognized group work as a preparation for the changing workplace, which is increasingly becoming collaborative (Collins et al., 1989). They felt that the laboratory and group experience provided them with skills that are increasingly important in a complex society.

Toward an Integration: A Grounded Theory

On the basis of the presented data, we derived a model for the students' conceptualization of physics knowledge and learning (Figure 1). At the top of the diagram we placed the continuum of epistemological commitments to which an individual's view of knowing and learning physics will be related. There are two major aspects of physics knowledge, CULTURAL and INDIVIDUAL. From the students' points of view, both the MATHEMATICAL and the CONCEPTUAL frameworks are culturally mediated and presented to them by TEACHERS and TEXTBOOK (on the left side in Figure 1). Students variously spoke of physics as "a frame of mind and a perception with which to regard facts," a conception of physics that is very close to Kuhn's (1970) notion of paradigm. Students indicated that the MATHEMATICAL and the CONCEPTUAL knowledge can be used in support of each other (see dotted lines in Figure 1). Students with a good mathematical foundation used equations and formulae as efficient organizers of their knowledge. Remembering an equation (MATHEMATICAL), they regenerated the CONCEPTUAL base supporting it. There were also students who indicated that the conceptual physics knowledge underlying mathematical equations and procedures strengthened their understanding of the mathematical manipulations (bidirectional link). Through the subject of physics, mathematics had become concrete. Usually, this knowledge was mediated by using some form of TEXT, provided either by the TEXTBOOK, or by the TEACHER in the form of lectures and blackboard notes, or in additional readings. To acquire mathematical knowledge, both MEMORIZATION of equations and much PRACTICE are needed. To know the conceptual knowledge well, many students felt they had to memorize. In any case, when physics knowledge is viewed as being transmitted by teachers and textbooks in the form of texts,

FIGURE 1

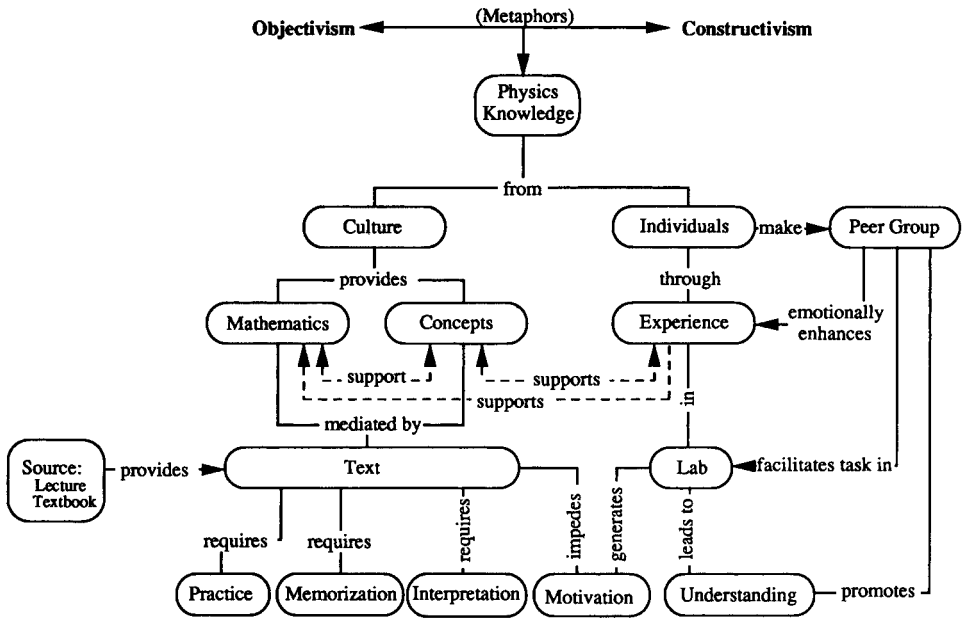

Figure 1. Students' epistemologies and views of knowing and learning physics: A grounded theory.

students felt in a receiving mode, which they disliked for learning the subject matter (impedes MOTIVATION).

The second major aspect of physics knowledge is its tie to personal experience (INDIVIDUALS). In part, this knowledge is intuitive. Physical principles are EXPERIENCED every day because we live in a physical universe. In part, this knowledge can be constructed in the LABORATORY. When knowledge is constructed in this way, it leads to UNDERSTANDING, an understanding that the textbook made of learning physics cannot provide. The direct EXPERIENCE of physics principles may also support the understanding of MATHEMATICAL and CONCEPTUAL knowledge as portrayed in the textbook or by the teacher (horizontal dotted lines in Figure 1). Many students realized, however, that without conceptual knowledge from the text, they would have to re-invent physics completely. Thus, they recognized that conceptual knowledge from the text could facilitate the learning of new principles in the lab (bidirectional link). Equally, although knowledge is generated by individuals, the PEER GROUP was considered an important feature of learning in the laboratory. First, it enhanced individual EXPERIENCE; through discussions and the consideration of multiple points of view, students could discover more on their own and were less dependent on the teacher. The peer group also facilitated the TASK itself, thus freeing the individual to become involved in the understanding side of a lab. Finally, the peer group could bootstrap its performance through negotiation of discrepant interpretation, through peer teaching and learning to new levels of understanding. This mode of learning physics, through individual construction and support of a peer group, was considered highly MOTIVATING.

From an epistemological point of view, the two perspectives are incommensurable. The

students clearly talked in terms of the conduit metaphor about the knowledge mediated by teachers and textbooks. As pointed out before, this metaphor, which describes learning as a process of information transfer from an authoritative source to a passive learner, is commensurable with an objectivist view of human knowledge. On the other hand, the students described learning in the laboratory in terms of (a) individual construction of meaning, (b) negotiation of idiosyncratic understanding and interpretation in peer groups, and (c) connections to prior knowledge and the intuitive cognitive framework derived from everyday experience of the physical world. This conception of learning was commensurable with a constructivist view of knowledge, according to which (a) understanding is constructed individually and negotiated in a social forum and (b) knowledge is meaningful and well integrated in the overall conceptual framework of the student. These incommensurabilities between students' views of knowledge and their preferred modes of learning resonate with those described in the section on the nature of knowledge. Although students predominantly portrayed scientific knowledge as absolute, as being or approximating truth, and as existing independently of people, they admitted social influences on the work of the scientist.

Conclusions

Data provided in this study indicate that the students held views that are not all concurrently commensurable with the same epistemological position. A student who claimed that scientific knowledge approximates truth and exists independently of human conceptualization could also maintain that scientific knowledge is a function of the scientists' social environment, as well as maintain a preference for studying science in a self-directed inquiry laboratory where discrepant interpretations are negotiated. These results could be interpreted as though students compartmentalize their knowledge so that they can hold incommensurable views without realizing this conflict (Davis & Mason, 1989; Lederman & O'Malley, 1990). However, a different interpretation based on the work of Belenky et al. (1986) places the origin of these incommensurable views in the transitory nature of students' epistemological commitment.

Both culture in general and school in particular play critical roles in determining students' views about the nature of knowledge. The traditional view of learning makes use of a conduit metaphor, reinforced by the information-processing views of cognition and by the impact of modern information carriers such as television. According to this metaphor, knowledge is transmitted from a sender to a receiver. In Western culture, and with it in much of traditional schooling, this metaphor is so pervasive that the predominant verbs describing learning are based on it. Children, being in part the product of culture, learn to use these metaphors. However, the metaphors we use also shape our world (Lakoff & Johnson, 1980). This relationship between internal and external worlds was emphasized in the formulations of constructivism by both Piaget and Goodman. In this respect, Piaget claimed that "Intelligence organizes the world by organizing itself" (cited in von Glasersfeld, 1984, p. 24), whereas Goodman (1978) held that "Comprehension and creation go together" (p. 22). The conduit metaphor is deeply rooted in objectivism, the myth of an external reality that can be objectively known and about which we can make objective and unconditional truth statements. For children growing up in Western society and attending its schools, objectivism is thus the predominant or the only epistemology available and thus becomes the "default epistemology." Students in this study were very much the product of this society and of traditional teaching. At the same time, the students viewed learning differently, which may have been the product of the different learning environment of the physics course in the context of this study. However, from our constructivist perspective, the search for and testing of simple cause-effect relationship was not meaningful so

we did not try to test an effect of the learning environment on student epistemologies. Key features of this environment were (a) small-group discussions, (b) student-generated research topics and investigations, (c) evaluation procedures that emphasized students' reasoning and divergent interpretation over "correct results," and (d) encouragement of active involvement. It is reasonable to assume that, influenced by this new experience—the teaching methods that varied from their other school experience and the implicit assumptions about the origin and nature of knowledge—changes occurred in students' conception of knowledge and learning.

In the students' language about learning, we can see a predominance of the objectivist conduit or conveyance metaphor (Lakoff & Johnson, 1980; Davis & Mason, 1989). According to this metaphor, the mind is a container; thoughts, ideas, and knowledge are entities that can be put, stored, or drilled into this receptacle. Communication—and teaching is one form of communication—involves an individual taking the knowledge out of his or her container and transferring it to another person, who can store it in turn. Such a conception of learning, however, is in conflict with much of current thought in epistemology, history and philosophy of science, cognitive and social psychology, philosophy, or sociology of science, which tends to focus on learning as a process of personal construction. Constructivist teachers view themselves as gardeners, tour guides, learning councilors or facilitators rather than as dispensers of information or judges of right and wrong answers. It is easy to see that if both the expectations of a constructivist teacher and those of students thinking in terms of the conduit metaphor are not met, doors are opened for much frustration and misunderstanding. It is not simply a matter of beginning to teach in a constructivist manner, but one can expect complex processes to occur in the ecology of the classroom, which includes both physical and social environment. As pointed out earlier, much of the research focused exclusively on teacher epistemologies, but neglected the more or less subtle changes through which the students have to go to adapt to a radically new conception of learning.

The present learning environment was also conceptualized as a nonlecture, inquiry-oriented context. This context is often advocated as ideal for developing students' ideas about the nature of science and, with it, about the nature of scientific knowledge. In our view it is possible that the nature of the laboratory situation in this school was responsible for the students' partly incommensurable views. Lederman and O'Malley (1990) question such benefits from laboratory instructions and contend that students do not develop the notion of the tentativeness of scientific knowledge in such a context. However, it is not the laboratory context as such that is responsible for the development of an epistemological stance, but the way these labs are taught. Laboratory exercises that follow a traditional "cookbook" format, where students simply follow predetermined procedures to verify laws and relationships, endorse an objectivist epistemology. Laboratory activities in which open inquiry, discussions and negotiations, and collaborative interpretation are central foster a constructivist epistemology.

The present data also support the contention that a transition is not made easily. The students had been studying in a climate that supported group work, negotiation of interpretations and meaning, whole-class discussion of discrepant results, and a disinterest for "right answers," yet two thirds of the students were committed to the view that scientific knowledge is exact, not tentative, and that it is independent from human conceptualization. Similar findings were reported by others (Solomon, 1991). In contrast, Lederman and O'Malley (1990) reported that all of their 16 interviewees believed in the tentativeness of science. We found, however, that "tentativeness" can still be associated with a view commensurable with objectivism. Thus, students who expressed such views simultaneously believed that theories may not fit at one time and thus are tentative. But, by improving their methods and technology, scientists would increasingly approximate truth.

The group of students in this study was distinct from other student populations in two aspects. Participants were all male and college-bound physics students. In the light of the Belenky et al. (1986) study, one would expect that a much higher proportion of students in a female group would be in transition to, or committed to, a constructivist relativist view of knowing. Also, it is possible that students inclined toward science are more committed to the dominant default epistemology, objectivism, than are those with a penchant for such subjects as the arts, language, and drama. However, only further research with groups distinctly different from ours will provide answers to these issues. Magnet, private, and alternative schools are potentially suited for studying distinctly different populations.

As educators and teachers we are asking ourselves about the implications of the present findings for the classroom. If the epistemological development is partly a factor of age, then we could simply wait for the students to become constructivists, the most mature epistemological commitment in both the Perry (1970) and the Belenky et al. (1986) schemes. For us as practitioners, this is not a satisfactory solution. However, simply exposing students to an environment in which a constructivist epistemology is implicit may not be sufficient, although constructivist curricula and learning environments raise students' interest in the way they learn science (Solomon, 1991). Time should be provided to discuss the historical precedents of scientific theory building, the social issues of science, and the plurality of languages for describing reality. And science teaching should help students make explicit, and reflect on, their own learning. A supportive environment sensitive to students' achievement needs must be a crucial ingredient to facilitate the changing epistemological climate. At present we are engaged in a teaching experiment to discover what happens to student epistemologies under these conditions. There seem to be considerable shifts in the students' views of scientific knowledge toward a more constructivist-relativist stance and a more critical perspective toward the image of science portrayed in textbooks.

Although we answered some questions with respect to students' epistemologies, their views of physics, and their ideas on learning science, other questions remain for future research. Among the more pressing ones are: What epistemological and learning preferences are characteristic for female students, students in co-educational classes, or students in science magnet schools? How do students' and teachers' epistemologies and views of learning interact in the context of science courses? How do changes in a teacher's epistemology affect the views of students? If students experience a change in their epistemologies do they also change their views on learning? What changes in students' epistemologies and views on learning come about if alternative epistemologies are discussed and serve as a frame for their own learning and experiences?

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