SCIENCE EDUCATION: IT'S NOT ENOUGH TO 'DO' OR 'RELATE'

BY KATHLEEN J. ROTH

ELEMENTARY SCIENCE teaching has not changed much in the last forty years; it was, and is, basically fact oriented and didactic. Textbooks present science as a large body of knowledge, and science learning involves memorizing facts about dinosaurs, planets, weather, etc. A crowded elementary curriculum and elementary teachers' lack of expertise in science pose an additional, enduring problem: Very little instructional time is allotted to science teaching. Reformers have not been satisfied with a science curriculum that emphasizes recall of facts, and this dissatisfaction has led to a series of attempts to change the nature of elementary science teaching. Each of these efforts has attempted to help students develop higher-order thinking skills—to think scientifically.

By far the most serious and best supported of these reform attempts was the inquiry movement in the 1960s and 1970s, which gave rise to extensive National Science Foundation programs in curriculum development and teacher education. By the 1980s, however, it was apparent that the inquiry movement had failed to achieve its goals. Teaching practice and commercial materials had adopted some of the rhetoric of inquiry teaching but had not changed their basic character and had not had a significant impact on student learning outcomes.

Thus in the 1980s the reform movement split into three groups: a) a still-powerful group that continues to advocate inquiry teaching, (b) a Science-Technology-Society (STS) group that focuses on changing the goals and content of science teaching, and (c) a conceptual change group that focuses on changing the methods of instruction so that they are more responsive to students' thinking and development. All of these groups agree on the need for reform and on goals that emphasize the development of conceptual understanding and higher-level thinking skills. Advocates of the three perspectives, however, differ in their definition of the relationships among content, process, and attitude goals; in their analyses of the nature of scientific thinking; and in their recommendations about what elementary children can and should be taught about science and the nature of scientific thinking.

Each of the three perspectives contrasts with traditional elementary science teaching in that they each select particular goals for focus and suggest a framework to help teachers focus on meaningful outcomes, instead of trying to "cover it all." While it is tempting to think about ways to blend the three perspectives, in this analysis I will stress the *distinctions* among them. I argue that elementary teachers need a framework or instructional model that helps them limit and focus their teaching on meaningful, achievable learner outcomes; telling teachers to "do it all" is counterproductive. An eclectic approach to science instruction (throw

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in a little bit of everything) is all too evident, I fear, in most elementary science textbooks in use today.

A brief description of typical textbook-based instruction will be used as a point of contrast with the three alternative perspectives. To provide additional points of contrast, examples of how each perspective might organize instruction to teach fifth graders about plants and photosynthesis will be described.

TRADITIONAL TEXTBOOK-BASED SCIENCE TEACHING

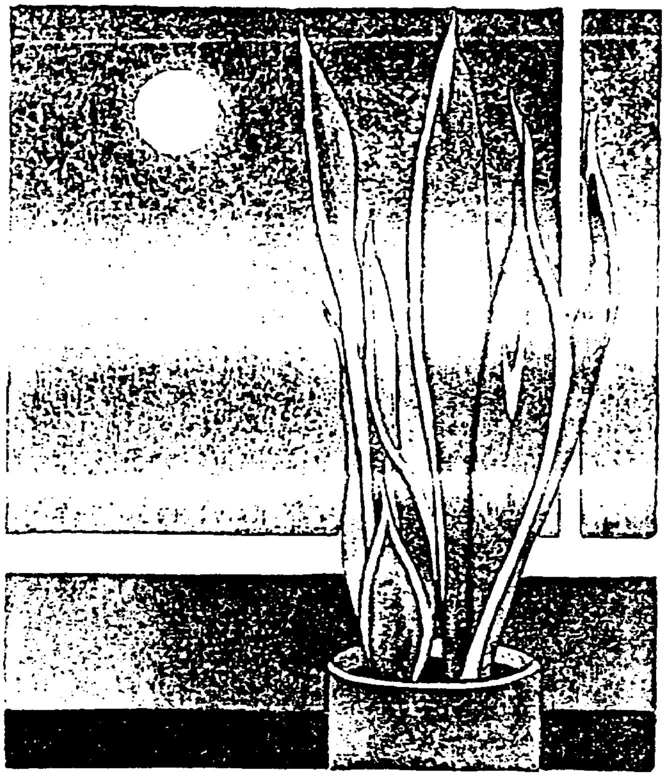
The traditional method of teaching science is focused on textbook instruction and didactic teaching. This content-mastery approach to science is organized around discrete topics—planets, electricity, magnetism, dinosaurs—with little attempt to make connections across topics. The instructional pattern typically consists of reading the text followed by answering factual questions posed by either the teacher or the text. Hands-on activities and teacher demonstrations are added to foster motivation but are often selected because they are easy to do or fun rather than for their usefulness in developing conceptual understanding or higher-level thinking. Thus, science teaching (and scientific thinking) is viewed as student acquisition of facts.

In the Silver Burdett & Ginn *Science* series (Mallinson, Mallinson, Valentino, & Smallwood, 1989), for example, fifth graders learn about photosynthesis in a chapter that presents a smorgasbord of information about activities of green plants. In five lessons, students learn about life processes: transportation of materials in plants; functions of roots, stems, and leaves; structure of leaf and stem cells (veins, stomata, chloroplasts, chlorophyll); the process of photosynthesis (role of energy, water, carbon dioxide; products); storage of manufactured food in fruits and vegetables; use of food energy in respiration; comparison of respiration and photosynthesis; and the use of energy for reproduction (parts of the flower, pollination, fertilization, germination). Thus, a wide spectrum of content is covered at a rapid pace.

In the lesson about photosynthesis, students read detailed information about the cell structure of leaves. The five steps in the photosynthetic process are listed and summarized in a word equation (water + carbon dioxide + energy → sugar + oxygen). To "evaluate student understanding," teachers are directed to ask factual questions that can be answered in short phrases taken directly from the text: What does a plant need to make food? (water, carbon dioxide, light energy) (Mallinson et al., 1989, p.12).

In a suggested enrichment activity, students look at leaf cells under a microscope. They draw cells and label the chloroplasts. In this lesson on photosynthesis, students read a lot of information and reproduce it in small bits when prompted by teacher questions. Only in a review question at the end are students required to explain anything (How do green plants make food?). The lesson does not ask students to use photosynthesis to explain everyday observations of plants or even to explain their observations in the enrichment activities.

Eighty-nine percent of the students in our study [of the inquiry method] failed to grasp the central concept of the unit.



The lesson on photosynthesis is followed by a lesson on plant respiration and a lesson on plant reproduction. This sequence of lessons does not seem likely to foster conceptual understanding and higher-level thinking. Instead, instruction is a parade of lessons marching along at a brisk pace, inundating observers (students) with a panoply of facts and concepts to be absorbed.

INQUIRY PERSPECTIVE

The inquiry perspective contends that students will develop better understandings of the nature of science and will be more interested in science if they are engaged in "doing" science. Student investigations of phenomena (not textbooks) are the backbone of the curriculum, and the focus of these investigations is on the use and development of science inquiry or process skills—predicting, hypothesizing, observing, recording data, making inferences and generalizations, etc. Students are viewed as little scientists who explore phenomena through hands-on activities and who use and develop scientific thinking skills to build up knowledge and conceptual understandings in the same ways that scientists use experimental work to construct new knowledge, concepts, and theories.

The proponents of an inquiry orientation acknowledge that science content and science thinking processes are both important, interrelated parts of science. They place a clear emphasis on the science thinking skills, however, allowing science content to play a secondary role. In the Elementary Science Study (ESS) materials (Educational Development Center, 1971), content is seen as almost irrelevant. The important thing is that children are engaged in scientific thinking and actions: asking questions, manipulating materials, observing phenomena, and making up explanations to answer their questions. Students "mess about" with mealworms or batteries or mystery powders, and the particular facts or concepts that they learn from these activities are not nearly as important as the lessons they learn about the nature of scientific inquiry.

In an inquiry perspective, the science process skills are generally regarded as the heart of scientific thinking, and these skills are typically organized in a hierarchical fashion. For example, the developers of *Science—A Process Approach* (SAPA) identified thirteen science processes and organized them in a hierarchy according to students' cognitive development (Commission on Science Education of the AAAS, 1968). Processes such as observing and classifying were seen as appropriate to teach at the early elementary level. Integrated process skills (hypothesizing, controlling variables, interpreting data, etc.) were deemed more complex and appropriate for the intermediate grades. Others organize these skills in a hierarchy that matches inductive models of a scientific method.

What is striking in the inquiry-oriented literature on higher-level thinking skills in science is the careful attention paid to describing and sequencing the science thinking process skills and the relative isolation of these thinking skills from a conceptual context. Little attention is given to the nature and development of scientific conceptual understanding. There is an underlying assumption that scientists' development of conceptual knowledge is a straightforward process: that conceptual knowledge is simply the "product" of the scientific thinking processes.

In an inquiry-oriented curriculum, science process skills are the main goal of elementary science teaching. Higher-level thinking is promoted by engaging students in using science processes in hands-on investigations. Content knowledge, conceptual understanding, and positive attitudes toward science are viewed as outgrowths of the inquiry investigations. The focus of instruction is on the development of process skills. If students can understand and use these general thinking process skills, they will be able to develop meaningful conceptual understanding in any area of study.

PHOTOSYNTHESIS IS the focus of the fifth-grade "Producers" unit in the SCIIS *Communities* Teacher's Guide (Knott, Lawson, Karplus, Thier, & Montgomery, 1978). In this unit, three major activities serve as the focus of classroom lessons, and no textbook is used. First, students germinate and measure the growth of various seed parts. This activity is designed to illustrate that germinating seed embryos get food from the seed.

In a second activity, students plant grass seeds and keep some in the light and some in the dark to demonstrate that plants need light to grow and to suggest that plants do not get food from the soil. Toward the end of this activity, the teacher explains photosynthesis to the students and the experiment is interpreted in light of this explanation. Finally, students germinate and measure the growth of bean plants under various conditions: with and without cotyledons (the developing embryo's food supply in the seed) and with and without light. Students are expected to use the idea of photosynthesis to explain their results.

Ms. Kain (pseudonym) and three other teachers whom we observed in our study (Roth, 1984; Smith & Anderson, 1984) spent six to eight weeks teaching this unit. In each of these classrooms, the bulk of instructional time was spent on setting up the experiments, measuring plants, recording results on a class scatter plot, and using the scatter plots to average data and draw line graphs to show patterns of growth. Discussions were also important aspects of lessons. Ms. Kain's questions focused on eliciting students' predictions, observations, and explanations of the experiments. She rarely gave out information, explaining photosynthesis only once during the unit and once in a unit review. Thus, Ms. Kain created many opportunities and a safe environment for students to construct their own explanations of observed phenomena; she never drilled students about definitions or details of the photosynthetic process. She spent eight weeks exploring photosynthesis with her students (approximately twenty-four lessons), quite a contrast with the one-lesson coverage of the Silver Burdett textbook.

And what did the students learn? Our post-tests (Roth, Smith & Anderson, 1983) assessed students' conceptual understanding by asking a variety of questions about how plants get their food. Eighty-nine percent of the students in the study failed to grasp the central concept of the unit: that plants get their energy-containing food only by making it internally out of carbon dioxide and water. Instead, most students began and ended the unit believing that plants take in food from the outside environment and that plants, like people, have many different kinds of food (air, water, fertilizer, minerals, soil, sun, etc.). Students watched and measured plants growing in the light and the dark, they conducted the experiments with germinating seedlings, but they interpreted these observations in terms of their preconceived ideas and failed to integrate the teacher's presentations of photosynthesis into their interpretations of the experiments. At best, students added plants' making of food as one of *many* sources of food for plants, failing to understand the *unique* ability of green plants to use light energy to convert non-energy-containing raw materials into energy-containing food that is necessary to support growth and life functions. A similar pattern was seen in textbook-focused classrooms. Thus, an inquiry approach did not provide any advantage in promoting conceptual understanding.

AND WHAT did students learn about the nature of scientific inquiry, scientific processes, and scientific attitudes? Many of them found "doing" science (the science processes) "fun" but ended up frustrated by the focus on processes and by all the measuring and recording of data. As Rachel explained,

> I don't know *why* we kept measuring those plants. I mean it was fun for awhile, but I already know that plants need light, and now I know it again.

What did Rachel learn about science processes and scientific thinking? She learned that it involves a lot of activity that does not help you make any better sense of things. She learned that science activities and processes are ends in themselves. It is important, for example, to make careful observations and to record them accurately not because such care helps you develop better understanding but because "that's what you do in science." Because Rachel did not develop better conceptual understanding, the processes of science seemed meaningless and not worth the effort. Driver (1983) critiques this doing of science in the absence of meaningful conceptual development, suggesting that the "I do and I understand" slogan might more appropriately be "I do and I am even more confused."

The results of this study also suggest that involvement in hands-on activities did not produce the desired student *attitudes* toward science. Although the activities made science seem fun, they did not necessarily help students value and feel comfortable with science. As a learner, Rachel was clearly frustrated that the doing of science did not lead her to any better personal understandings about plants' need for light. Although she was in a classroom environment where her ideas were valued and where she felt comfortable sharing her ideas, Rachel did not leave the unit feeling good about herself as a learner of science or comfortable in the neighborhood of science. She wondered why she held the same understandings at the end of the unit that she had held at the beginning. She had spent eight weeks measuring, observing, and talking about plants, and no change in her understanding had occurred! This was not a satisfying learning experience for her nor was it an experience that will make her enthusiastic about studying more science. These findings suggest that assessments of student attitudes toward science must dig beneath the surface; it is not enough to know that students have positive attitudes toward hands-on activities. What are they learning about science and scientific thinking?

SCIENCE-TECHNOLOGY-SOCIETY PERSPECTIVE

Many science educators advocate a dramatic change in the goals of K-12 science education. They argue that the overarching purpose of school science is not to create future scientists but to create citizens who understand science in multidimensional, multidisciplinary ways that will enable them to participate intelligently in critical thinking, problem solving, and decision making about how science and technology are used to change society (environmental issues, nuclear power, personal health, energy resources, etc.). Yager and Hofstein (1986) describe this perspective in sharp contrast to both the traditional, disciplinary-based focus of science teaching and to the inquiry approach:

> In some respects the traditional content and process dimensions of science may be the dimensions least important and appropriate to us in planning for the year 2000. They may be least important for helping us attain a scientifically and technologically literate citizenry for which so many yearn. If so, they may be the dimensions of science that deserve little or no emphasis as a science curriculum is planned and newly conceived for all K-12 students.

Yager and Hofstein suggest six essential goals of a quality K-12 science curriculum. These goals stand in clear contrast with those espoused by the inquiry perspective:

> 1. The human being, human potential, human advances, and human adaptations will serve as the organizer of the curriculum (instead of the structure of the disciplines or the scientific processes).
> 2. Current problems and societal issues will serve as the backbone of the curriculum.
> 3. Science and technological processes that students can use in everyday life will be emphasized over processes that scientists use.
> 4. Practice with decision-making skills using science and technology knowledge in a relevant, social context will be emphasized over skills needed to "uncover correct answers to discipline-bound problems."
> 5. Awareness should be an integral part of science learning.
> 6. In dealing with problems and issues, ethical, moral, and value dimensions will be considered (in contrast with traditional science instruction, which is taught as value free and discipline bound).

Thus, an STS curriculum is human and society focused, problem centered, and responsive to local issues. Problems to be investigated are selected for their relevance to students' lives and their multidisciplinary nature. As in the inquiry perspective, students are seen as active learners, but the activities they engage in are focused on *using* scientific and technological knowledge to solve problems and make decisions rather than on *creating* scientific knowledge. Thus, in the STS perspective, students act as young science citizens rather than young research scientists.

THE STS PERSPECTIVE shares with many of the inquiry programs a tendency to separate process goals from content goals and to emphasize process goals over content goals. Content is to be selected based on its interest and relevance for students and on the richness of the societal problem it provides. Thus, content is selected for its potential to serve the primary goals of developing students' decision-making and problem-solving process skills and of helping students learn to integrate values and moral thinking in this decision-making process.

Thus, process or thinking skills are of primary importance in the STS perspective, but the process skills are

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defined quite differently from those in inquiry programs. The processes emphasized in the STS perspective focus on wise *use* of scientific knowledge in decision making and problem solving about societal problems rather than on the construction of scientific knowledge through careful observation, inferencing, experimentation, etc.

In the STS perspective, decision making and problem solving are viewed as the higher-level thinking skills that students should develop. These skills are seen as needed by all students, not just those bound for science careers. To "think scientifically," then, one does not need to be able to create or discover scientific ideas the way a research scientist does. Rather, one needs to be a good consumer of scientific knowledge—finding and using scientific ideas as needed to solve particular problems.

As in the inquiry perspective, there is a striking lack of analysis in the STS literature about the particular content or concepts needed to make good decisions or to solve problems. The kinds of conceptual knowledge needed to do effective decision making and problem solving have not been carefully analyzed or defined. This lack of attention to the nature of conceptual understanding suggests an assumption that the conceptual knowledge needed to think scientifically (to make decisions and to solve problems) is straightforward information that students will rather easily incorporate into their own thinking. Thus, the challenge (or higher-level aspects) of scientific thinking is not in understanding concepts but in using concepts to make decisions and solve problems.

SINCE MATERIALS from an STS perspective are only now in the development phase, I will speculate about a possible STS unit on photosynthesis. A science-technology-society unit would probably not teach about photosynthesis as the focus of a unit. Instead, photosynthesis would be addressed in the context of exploring a technological or scientific problem facing society. For example, a unit might be structured around the problem of the effects of deforestation and industrialization on the warming of the Earth's atmosphere due to the greenhouse effect. Science concepts relevant to this problem include absorption of solar energy by the Earth's atmosphere and the changing balance of O_2-CO_2 in the Earth's atmosphere due to fossil fuel use and widespread cutting of rain forests (plants use carbon dioxide in the photosynthetic process and release oxygen). The teacher would help students use these concepts to assess the severity of the problem and to think about possible solutions to the growing danger of the greenhouse effect: Should the chopping down of rain forests be slowed down? How? Why would developing nations resist pressures to slow deforestation? What are other ways of slowing the greenhouse effect? How can local citizens influence decisions about slowing fossil fuel usage?

Unit activities might focus on role playing and assessment of the problems from different points of view. Scientific processes could be investigated in the context of studying the evidence that the greenhouse effect is actually a danger. Students might read arguments from scientists holding different opinions about the severity of the threat. The unit-culminating activity would be a student-generated activity designed to take action on these issues, such as writing and circulating a pamphlet about ways to reduce energy consumption in the home, studying home gas and electric bills and trying to decrease consumption for a month, writing to state representatives or members of Congress in support of particular bills related to energy issues, and planting trees on school grounds and encouraging others to plant trees.

In this approach, students would be engaged in complex thinking that requires them first to understand and evaluate the soundness of the evidence offered by expert scientists and then to integrate those understandings with understandings of social and political processes. For the unit to be meaningful and to result in student generation of a worthwhile project, the role of the teacher would be a very complex one. Teachers would have to understand underlying scientific principles, the evidence supporting scientists' predictions of the greenhouse effect, and the relationships between political and scientific issues.

The knowledge that students are likely to learn about photosynthesis in such a unit would be limited in the traditional disciplinary sense. For example, discussions of photosynthesis are likely to focus on CO_2-O_2 balance rather than on the food-making function. Because the unit activities focus on problem solving and citizenship action, students are more likely to end the unit understanding that extensive cutting of forests and burning of fossil fuels may result in warming climates worldwide rather than remembering much about photosynthesis. Helping students see how science and technology can both cause problems and help solve problems would be another challenge in teaching this unit. Without such an appreciation, students might come to view science and technology as evil and threatening. Thus, they would not value scientific inquiry and knowledge generated by science.

Conceptual Change Perspective

Of the three perspectives, the conceptual change perspective is the only one that did not originate in response to a social/political climate that demanded reform in science education. In contrast, it is a research-based perspective that grew out of cognitive science studies of learning and knowing in knowledge-rich domains. Research on teaching and learning in science, in particular, provided critical insights about why it is so difficult for students to develop useful, conceptual understandings of many of the subjects they are taught in school (Anderson and Roth, in press; West and Pines, 1985).

In a conceptual change perspective, the primary goal of science education is to help students develop meaningful, conceptual understandings of science and its ways of describing, predicting, explaining, and controlling natural phenomena (Anderson and Roth, in press; Driver, 1987). In this view, scientific knowledge is meaningful to learners only when it is *useful* in making sense of the world they encounter.

Scientific knowledge that can be used by learners is characterized by rich connections between concepts and facts and is organized around key ideas in ways that make the knowledge accessible and able to provide broad explanatory power. This stands in contrast to knowledge that exists as isolated fragments that students can parrot back for recall-focused tests but cannot apply in explaining real-world phenomena. Such connected knowledge is not locked into one tightly organized structure that simply gets larger as a learner adds new knowledge into it (a passive, additive view of learning and a static view of knowledge). Rather, this set of connected knowledge is flexible and constantly changing as the learner revises, reorganizes, and deepens understandings over time (an active, conceptual change view of learning and knowledge growth).

This web of knowledge, or the individual's conceptual ecology (Posner et al., 1982), only becomes useful and meaningful to students when it is integrated with the learners' own personal knowledge and experiences with natural phenomena. Students come to science classes with many ideas and explanations about natural phenomena. Their ideas are experience based and often stand in stark contrast to the scientific explanations studied in school. A central goal of science teaching is to help students *change* their intuitive, everyday ways of explaining the world around them—to incorporate scientific concepts and ways of thinking into their personal frameworks.

Like the STS advocates, advocates of a conceptual change perspective argue that a central goal of science education is to develop scientific literacy for *all* students. The two perspectives, however, define the nature of a scientifically literate society in different ways and they suggest different instructional approaches. The conceptual change perspective focuses on the power of conceptual understanding, arguing that the way to develop scientifically literate citizens is to change instruction so that it helps learners develop rich and meaningful understandings of whatever science they study. Such understanding will help students value science as a sense-making endeavor. The STS perspective, in contrast, approaches the need for a scientific citizenry from a curricular perspective, arguing that it is changes in the *content* of the curriculum that are critically needed. To capture the interests of all students, traditional disciplinary-bound curricula need to be abandoned in favor of current science and society issues.

Unlike the inquiry and STS perspectives, the conceptual change perspective views conceptual knowledge as central in science and in science learning. Where do the scientific processes fit in this scheme? Scientists' work, this position argues, is conceptually driven, and the so-called scientific processes cannot be separated from scientific conceptualizations. Science teaching, therefore, should integrate science processes and conceptual knowledge in ways that better reflect the richness and complexity of science itself.

WHAT DOES it mean to say that scientists' work is "conceptually driven"? Expert scientists do not hypothesize, make inferences, or design experiments in the absence of conceptual frameworks. Their conceptual frameworks are not only influenced by their observations and inferences; their frameworks also *drive* and shape the hypotheses they make, the questions they raise, the things they pay attention to in their observations. What distinguishes their work as science is not these processes, which are processes that are equally applicable in history, economics, mathematics, or the arts, but the particular knowledge that organizes how these processes are used. A scientist who observes well, for example, is not one who spends endless hours documenting and describing every possible detail that can be observed about a particular phenomenon. Instead, a good scientific observation focuses on key features in ways that will contribute new knowledge, that increases the explanatory power of a particular

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The unit began by eliciting students' definitions of "food." The text explained the difference between everyday definitions of food (anything we eat or drink) and a definition of food as energy-containing matter. After agreeing that water is not food by this definition, the students became involved in a lively debate about how plants get their food. Most students asserted that water is one important food for plants, while others pointed out that water does not have energy in it. Students had interesting experience-based arguments to support their belief that water did provide energy for *plants* ("rain water has energy in it but drinking water doesn't"). The class made a chart listing their ideas about how plants get their food, and this chart was revisited several times throughout the month-long unit.

Two hands-on experiments (adapted from the SCIIS "Producer's" unit, Knott et al., 1978) and one discussion of a historical experiment provided initial information to help students puzzle through the problem of how plants get their food. An experiment with germinating seed parts suggested that young plant embryos get food that is stored in the seed's cotyledon. In discussing the results of this experiment, the idea that water did not contain energy for plants was again discussed. But many students still made predictions in the next experiment that grass seeds would grow in both light and dark conditions if they were watered because water is their food. Water was still a confusing issue.

While the grass seeds were given time to grow, von Helmont's famous experiment of 1642 was read and discussed. Students' predictions agreed with von Helmont's: As the tree in the tub of soil grows, the weight of the soil will decrease as the tree "eats" materials from the soil. When the students found out that the soil in von Helmont's experiment did not lose any significant weight, they accepted this as evidence that the plant was not "eating" soil. But they remained puzzled about why plants need soil and what fertilizers and minerals do for plants. I encouraged these questions while trying to keep the students focused on the problem of how plants get energy-containing food. As the grass plant experiment proceeded, and plants in the dark began to yellow and die, students became increasingly convinced that sunlight was somehow important and unsure about the role of water. Clearly, soil and water *alone* could not keep a plant alive. The sun seemed to be very important. But is the sun itself the food for plants, as many students believed?

Only when most of the students' entering ideas about food for plants had been either ruled out or brought into question was an explanation of photosynthesis given: that cells in plants' leaves use light energy from the sun to change water and air into energy-containing food. After this idea was explained in contrast with students' entering ideas, students were given many opportunities to use photosynthesis to explain everyday phenomena. In addition, their own application questions were rewarded and encouraged. One student, for example, wondered about the fact that *only* plants could make food. Did that mean that without plants, there would be no food? Another countered that we could live on candy bars if we didn't have plants. I encouraged this debate and later brought in Snickers bars. We analyzed the list of ingredients, talking about how each ingredient (corn syrup, sugar, peanuts, chocolate) had been made by a particular kind of plant.

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Application opportunities included problems posed in overhead transparencies (How did this plant produce a potato?), questions posed for students to write and/or talk about (What if only one leaf of a plant could get sunlight? Could it live? Why or why not?), and further experimentation. Students also wrote in science log books about their evolving ideas, receiving feedback questions and comments from the teacher. Application activities included analysis of controlled experiments as well as other, seemingly nonscientific activities, such as role playing the life of a bean seed embryo. Card-sorting activities where students constructed (in pairs and individually) different concept maps showing the relationships among ideas were also used.

At the end of the unit, students revisited their initial explanations of how plants got their food and wrote and talked about how their ideas had changed. The post-test asked a series of application questions for which students had to write out predictions and explanations. There was also a mini-interview question in which students were asked to arrange words related to photosynthesis (air, water, sun, fertilizers, soil, colyledon, leaf, stem, etc.) in a conceptual map and then explain their arrangement. Most students demonstrated a coherent understanding of the key concepts; the interviewer questions permitted individual coaching to clarify remaining confusions. Students' comments and questions revealed ways in which their conceptual understanding had generated a new sense of wonder and sense making:

> John: Ms. Roth, I used to think that plants were just kind of *there*, ya' know? They just sat there. But now I know that they're really very busy little things, aren't they? There's lots going on inside them.
>
> Ted: I know plants can use water, air, and sun to make food . . . . but, I mean, *how* do they do that?

This unit involved much more time than the one lesson on photosynthesis outlined in the Silver Burdett & Ginn text (Mallinson et al., 1989). And yet the unit did not present many of the technical terms covered in the Silver Burdett & Ginn lesson—chloroplasts, stomata, carbon dioxide, hydrogen. But students were able to make predictions and observations, to change and develop explanations, and to apply ideas in a meaningful time frame; that is, they were provided time to change their understandings. The instructional model proved both workable for me and productive of meaningful