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ABSTRACT

The document reviews the literature concerning the goals of elementary school science teaching. The review indicated a consensus among scientists and science education experts that elementary school science instruction should promote meaningful understanding of science concepts, processes, and attitudes. Students should not just be memorizing scientific facts; they should be developing higher order thinking skills. However, the experts differ in their descriptions of the kinds of higher level thinking that elementary children should develop. As a result, teachers are faced with long lists of goals that do not support them in providing coherent, meaningful science instruction. The paper argues that a coherent model that focuses on a limited set of goals may be more productive in helping elementary teachers provide meaningful learning opportunities for their students. It reviews three perspectives on science teaching that hold promise for providing such a framework; an inquiry perspective, a science-technology-society perspective, and a conceptual change perspective. The similarities and differences of the three perspectives are discussed and the paper concludes with personal reflections from the author's own teaching. (Author/CW)

Elementary Subjects Center
Series No. 12

Conceptual Understanding and Higher Level Thinking in the Elementary Science Curriculum: Three Perspectives

Kathleen J. Roth

Center for the Learning and Teaching of Elementary Subjects

Institute for
Research on Teaching
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Center for the Learning and Teaching of Elementary Subjects

The Center for the Learning and Teaching of Elementary Subjects was awarded to Michigan State University in 1987 after a nationwide competition. Funded by the Office of Educational Research and Improvement, U.S. Department of Education, the Elementary Subjects Center is a major project housed in the Institute for Research on Teaching (IRT). The program focuses on conceptual understanding, higher order thinking, and problem solving in elementary school teaching of mathematics, science, social studies, literature, and the arts. Center researchers are identifying exemplary curriculum, instruction, and evaluation practices in the teaching of these school subjects; studying these practices to build new hypotheses about how the effectiveness of elementary schools can be improved; testing these hypotheses through school-based research; and making specific recommendations for the improvement of school policies, instructional materials, assessment procedures, and teaching practices. Research questions include, What content should be taught when teaching for conceptual understanding and higher level learning? How do teachers concentrate their teaching to use their limited resources best? and In what ways is good teaching subject matter-specific?

The work is designed to unfold in three phases, beginning with literature review and interview studies designed to elicit and synthesize the points of view of various stakeholders (representatives of the underlying academic disciplines, intellectual leaders and organizations concerned with curriculum and instruction in school subjects, classroom teachers, state- and district-level policymakers) concerning ideal curriculum, instruction, and evaluation practices in these five content areas at the elementary level. Phase II involves interview and observation methods designed to describe current practice, and in particular, best practice as observed in the classrooms of teachers believed to be outstanding. Phase II also involves analysis of curricula (both widely used curriculum series and distinctive curricula developed with special emphasis on conceptual understanding and higher order applications), as another approach to gathering information about current practices. In Phase III, test models of ideal practice will be developed based on what has been learned and synthesized from the first two phases.

The findings of Center research are published by the IRT in the Elementary Subjects Center Series. Information about the Center is included in the IRT Communication Quarterly (a newsletter for practitioners) and in lists and catalogs of IRT publications. For more information, to receive a list or catalog, or to be placed on the IRT mailing list to receive the newsletter, please write to the Editor, Institute for Research on Teaching, 252 Erickson Hall, Michigan State University, East Lansing, Michigan 48824-1034.

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Abstract

This paper reviews the literature concerning the goals of elementary school science teaching. The review reveals a consensus among scientists and science education experts that elementary-school science instruction should promote meaningful understanding of science concepts, processes, and attitudes. Students should not just be memorizing scientific facts; they should be developing higher order thinking skills. However, the experts differ in their descriptions of the kinds of higher level thinking that elementary children should develop. As a result, teachers are faced with long lists of goals that do not support them in providing coherent, meaningful science instruction. In promoting a "do it all" approach, experts may be dooming teachers to failure. The author argues that a coherent model that focuses on a limited set of goals may be more productive in helping elementary teachers provide meaningful learning opportunities for their students.

The paper reviews three perspectives on science teaching that hold promise for providing such a framework or model--an inquiry perspective, a science-technology-society perspective, and a conceptual change perspective. Although the three perspectives share overlapping features, the descriptions emphasize the <u>differences</u> among them. A particular focus is on the contrasts in the ways in which higher level thinking and conceptual understanding are defined in each. Patterns of current elementary science teaching practice are contrasted with the three visions articulated by experts and reasons why current practice is so far removed from these visions are explored. The paper concludes with the author's personal reflection on the usefulness of a conceptual change perspective in guiding her own teaching of science to fifth-grade students.

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Preface

This is one of a set of seven reports being prepared for Study 1 of Phase I of the research agenda of the Center for the Learning and Teaching of Elementary Subjects. Phase I of our work calls for surveying and synthesizing the opinions of various categories of experts concerning the nature of elementary-level instruction in mathematics, science, social studies, literature, and the arts, with particular attention to how teaching for understanding and for higher order thinking and problem solving should be handled within such instruction. Study 1 of Phase I calls for review of the literature in educational psychology, cognitive science, and related fields on teaching for understanding and for higher order thinking and problem solving, as well as the literature on these topics as they are discussed by curriculum and instruction experts within the context of teaching particular school subjects. The present paper focuses on statements about teaching for understanding and for higher order thinking and problem solving in science that have been advanced by the leading scholars and organizations concerned with elementary-level science education.

CONCEPTUAL UNDERSTANDING AND HIGHER LEVEL THINKING IN THE ELEMENTARY SCIENCE CURRICULUM: THREE PERSPECTIVES

Kathleen J. Roth[1]

At a fall open house in 1975, I explained to the parents of my middle school science students that one of my goals for the year was to help the students learn how to "think scientifically." After my presentation, one of the parents came up to me and asked, "Do you really think that you can teach someone how to think scientifically?" That question triggered a whole set of questions for me about the purposes of teaching science: Is teaching children to "think scientifically" a realistic outcome of elementary and middle school science instruction? Or was that just rhetoric that sounded good when communicating with parents? And what did I mean by "scientific thinking"? What is the nature of scientific thinking? What can and should children be taught about scientific thinking?

I asked myself about the other goals on my list: To help students appreciate the beauties and complexities of the natural world, to help students develop more independence in their learning, to teach students basic concepts in the life sciences. How did these goals relate to the goal of teaching for scientific thinking? And how did all of these goals match with what I was actually doing as a teacher? Which of these goals were the most important, and which could be achieved in meaningful ways while working with a group of 26 students for two-three hours per week across a school year?

In the 14 years since that parent first challenged my thinking about the goals and purposes of teaching young children about science, I have explored

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[1] Kathleen J. Roth, an assistant professor of teacher education at Michigan State University, is a senior researcher with the Center for the Learning and Teaching of Elementary Subjects.

these questions in my teaching experience, in research projects in which I have studied classroom teaching and learning of science, and in my work with preservice and inservice teachers. These experiences provided me with new perspectives for thinking about the goals and purposes of elementary science instruction. They gave me insights both about what is possible to achieve and about the real constraints teachers face in trying to achieve the "possible." My classroom research efforts convinced me that it is possible to teach for "higher level" outcomes in science--to teach young children to think scientifically. But the research also revealed the complexities and challenges involved in teaching for such higher level outcomes.

However, my research-based insights about the difficulties of teaching students to understand concepts and to "think" scientifically seemed at odds with the statements from various groups of science education experts. The expansive lists of goals completed by experts baffled me. How could a teacher possibly work toward all of these goals in meaningful ways? In compiling these lists, how did the experts expect teachers to handle the contradictions between the far-reaching goals and local constraints of classrooms? Did they expect teachers to pick and choose from this list in order to deal with a few of the goals in meaningful ways? Or did the experts define "understanding" of concepts and of science thinking (process) skills in ways that would allow teachers to claim success when students were merely exposed to opportunities to understand concepts and to think scientifically?

As a step toward clearer and more realistic articulation of the desired outcomes of elementary science, I reviewed various experts' recommendations. In this literature review, I analyzed experts' explicit and implicit definitions of the nature of conceptual understanding and higher level thinking in science. What do different experts mean by "scientific thinking?" What does it mean to teach for conceptual understanding and higher level thinking in elementary science? How feasible is it to achieve such outcomes in elementary classrooms?

In this paper, I analyze the desired outcomes of elementary school science instruction from three perspectives that are currently advocated by different groups of science educators, educational researchers, and scientists. The three perspectives will be referred to as the inquiry perspective, the science-technology-society perspective, and the conceptual change perspective. The three perspectives share overarching commitments to the teaching of science content, (facts, concepts, generalizations, theories), science thinking processes (predicting, hypothesis-making, observing, inferring, etc.) and scientific attitudes, and their goals often overlap. However, each perspective does select particular goals for focus and does suggest a framework or model that could help teachers focus their planning and teaching on meaningful outcomes instead of trying to "do it all". Each perspective also emphasizes higher order aspects of scientific thinking as critical student outcomes. Thus, I believe each perspective is worth serious consideration for its potential to provide both a workable framework for teachers and a framework that has potential to promote meaningful understanding of science and scientific thinking for students.

In this analysis, I will push the <u>distinctions</u> among the three perspectives. It is tempting to think about ways that the three perspectives could be blended together to create a "super model". That may be a worthwhile long-term research effort, but I think it is a mistake to pick and choose from these without a sound theoretical, pedagogical, or research-based rationale. Such an eclectic approach to science instruction is all too evident, I fear, in most elementary science textbooks in use today. These texts <u>do</u> provide workable frameworks for teachers; teachers find them useful in selecting both content and instructional methods. And the texts do seem to "do it all"; they attempt to address all of the experts' recommendations. However, these texts do not help teachers plan and teach in ways that foster meaningful conceptual understandings and understandings of the nature of scientific thinking.

Thus, in this analysis I will focus on the differences among the three alternative perspectives, contrasting the desired outcomes emphasized from each perspective, the historical and theoretical development of each perspective, and the ways in which conceptual understanding and higher level thinking are defined in each. The definitions of higher order thinking are intimately linked to the ways in which each perspective views the relationships among science content, scientific thinking process skills, and scientific values and attitudes. These contrasts will be described. Ways of assessing student conceptual understanding and higher level thinking in each perspective will also be discussed. The assessment analysis serves two purposes: First, sample assessment items help clarify what counts as "understanding" in each perspective. Secondly, assessments of student learning completed in research studies provide some insights about the effectiveness of the inquiry and conceptual change perspectives. Finally, the vision of ideal elementary science teaching and learning that each perspective suggests will be described.

Although each of these three perspectives defines the terms differently, they share an emphasis on teaching for higher level thinking outcomes and for depth of understanding rather than breadth of coverage. However, studies of current elementary science teaching practice reveal a quite different picture. Patterns of current practice will be contrasted with the three visions articulated by experts, and reasons why current practice is so far removed from these visions will be explored. Such an analysis is critical in developing a realistic and useful framework for defining desired outcomes of science instruction.

The paper concludes with personal reflections about ways in which a conceptual change framework has been useful in guiding my efforts to teach for conceptual understanding in a fifth-grade classroom. Although I argue that this perspective has the potential to help teachers focus on teaching for conceptual understanding and a rich view of the nature of science, important questions about its limitations and usefulness remain. I conclude by raising these questions and suggesting ways in which these questions might be fruitfully explored.

Background: The Recommendations from Science Organizations and Experts

Many of the goal statements for science education written by expert groups of scientists and science educators and by authors of science methods textbooks suffer from attempts to be all-encompassing (American Association for the Advancement of Science, 1989; Bybee et al., 1989; Jacobson & Bergman, 1980; National Science Teachers Association, 1982; Rutherford, Ahlgren, Warren, & Merz, 1987; Simpson & Anderson, 1981; Wolfinger, 1984). As a result, these guidelines and position statements do not provide teachers and schools with a focused, manageable vision of good elementary science curriculum. Instead of advocating and developing such a vision, these statements are more typically a compilation of experts' opinions about ideal goals for science education. Such opinions are often summarized in rather lengthy lists which suggest that elementary science teaching should address multiple goals equally well. Because the experts did not tackle the difficult task of limiting or prioritizing goals to match classroom realities, the lists compiled by different groups reflect little disagreement. They agree that elementary science instruction should "do it all." Each group acknowledges multiple purposes and goals for elementary science instruction and typically organizes those goals into three categories: science content/knowledge, science processes/thinking skills, and scientific attitudes and values (Carin & Sund, 1980; Edwards & Fisher, 1977; Henson & Janke, 1984; Jacobson & Bergman, 1980; Farmer & Farrell, 1980; Wolfinger, 1984). Despite the experts' agreement about these goals, it is clear that we have not begun to achieve these kinds of student outcomes in schools. While all the goals are lofty ones that no one could disagree with, their all-encompassing scope contrasts sharply with the limited attention given to science instruction in elementary schools today.

Given the failure of present science teaching to accomplish these goals in meaningful ways for the majority of students, it is problematic that these lists of goals simply seem to grow longer over time. For example, in tracing the historical development of statements from the National Science Teachers Association (NSTA), I found a gradual addition of new goals (most recently, goals related to science-technology-society issues) with a shift in emphasis as new goals are added. However, earlier goals are not abandoned, redefined, or reconceptualized as new goals are added; instead, they are kept in the list but with new goals framing them. NSTA's list of goals for the 1970s (NSTA, 1971), for example, begins and ends with an emphasis on inquiry process outcomes. In the 1980s position statement (NSTA, 1982), these process goals remain but the list is framed with a new emphasis on science-technology-society goals (See Table 1). Lengthening the lists of goals in this way does not seem likely to provide a useful framework or vision for elementary science instruction.

These broad descriptions of what scientifically literate adults should be able to do sound on the surface like reasonable and clearly articulated goals. But there are at least two issues that need further exploration. First, the

Table 1

The National Science Teachers Association: Goals for K-12 Science Teaching in the 1970s and 1980s

Position Statement for the 1970s	Position Statement for the 1980s
The goal of science education should be to develop scientifically literate citizens with the necessary intellectual resources, values, attitudes, inquiry skills to promote the development of many as a rational human being. The scientifically literate person: * uses science concepts, process skills, and values in making everyday decisions as he interacts with other people and with his environment; * understands that the generation of scientific knowledge depends upon the inquiry process and upon conceptual theories; * distinguishes between scientific evidence and personal opinion; * identifies the relationship between facts and theory; * recognizes the limitations as well as the usefulness of science and technology in advancing human welfare; * understands the interrelationships between science, technology, and other facets of society, including social and economic development; * recognizes the human origin of science and understands that scientific knowledge is tentative, subject to change as evidence accumulates; * has sufficient knowledge and experience so that he can appreciate the scientific work being carried out by others;	Declaration The goal of science education during the 1980s is to develop scientifically literate individuals who understand how science, technology and society influence one another and who are able to use this knowledge in their everyday decision-making. The scientifically literate person has a substantial knowledge base of facts, concepts, conceptual networks, and process skills which enable the individual to continue to learn and think logically. This individual both appreciates the value of science and technology in society and understands their limitations. The attributes listed below help to describe a scientifically literate person. The scientifically and technologically literate person: * uses science concepts, process skills, and values in making responsible everyday decisions; * understands how society influences science and technology as well as how science and technology influence society; * understands that society controls science and technology through the allocation of resources; * recognizes the limitations as well as the usefulness of science and technology in advancing human welfare;

* has a richer and more exciting view of the world as a result of his science education; and

* has adopted values similar to those that underlie science so that he can use and enjoy science for its intellectual stimulation, its elegance of explanation, and its excitement of inquiry;

* continues to inquire and increase his scientific knowledge throughout his life

* knows the major concepts, hypotheses, and theories of science and is able to use them;

* appreciates science and technology for the intellectual stimulus they provide;

* understands that the generation of scientific knowledge depends upon the inquiry process and upon conceptual theories;

* understands the applications of technology and the decisions entailed in use of technology;

* has sufficient knowledge and experience to appreciate the worthiness of research and technological development;

* has a richer and more exciting view of the world as the result of science education; and

* knows reliable sources of scientific and technological information and uses these sources in the process of decision making

statements are vague about the nature and depth of student understanding that is desired. Second, the lists are overly ambitious given the present day context of elementary science teaching. Ways in which these characteristics of the statements are problematic are discussed below.

Nature and Depth of Desired Understandings

First, these goal statements are problematic in their lack of clarity about the nature and depth of desired student understanding of science content, thinking processes, and attitudes. What kinds of scientific thinking, particularly higher level thinking, about content, processes, and attitudes are the desired outcomes? What is the nature of thinking that we want students to develop? What does it look like when a fifth grader "understands" the concept of ecosystems? What does it mean to "know" the scientific processes? Is it sufficient that a student "likes" science, or should the student demonstrate the disposition to inquire and to think critically? These statements of desired outcomes provide only partial answers to these questions, and the answers are particularly sketchy at the elementary level. Most of these lists are written in terms of desired qualities of scientifically literate adults. They do not suggest what the understanding of a first grader's or fifth grader's understanding should or could be like. What does it mean for a first grader or a fifth grader to "know the major concepts, hypotheses, and theories of science" or to "use science thinking process skills"?

a. Content. Recommendations from these groups are particularly silent about the nature of content outcomes. In the 1960s efforts to articulate the central concepts and conceptual schemes that students should come to understand were undertaken. Current efforts by the American Association for the Advancement of Science (1989) are also focused on identifying central concepts that should form the core of the school science curriculum. These concepts were derived from an analysis of the respective science disciplines (biology, physics, earth science, etc.). Table 2 provides examples of such lists of concepts.

Beyond these efforts, however, the statements from these groups leave many questions unanswered. For example, how should content be selected and organized? Should content be selected because of its relevancy to students' experiences, because of its explanatory power within the discipline, or because it is content that every literate adult should be familiar with? Or should content be selected based on the teacher's expertise? Should content be organized topically (stars, plants, weather, etc.) as is done in most current science textbooks, or should it be organized around central conceptual schemes of science (matter and energy, interactions, etc.)? Or what about organizing the content around societal problems that science addresses? Or should the curriculum not be organized around content at all, but instead focus on the scientific processes? How should content goals mesh with process and attitude goals? Although the various goal statements use rhetoric about balancing and integrating content and process goals (NSTA, 1964 & 1982; Edwards & Fisher, 1977; Esler & Esler, 1981; Farmer & Farrell, 1980; Rowe, 1978;, Wolfinger, 1984), they provide little vision of what the student who understands the goals in such integrated ways would be able to say or do. In addition, what do these lists of concepts communicate about breadth of the curriculum? Do all of the concepts need to be covered in a K-6 curriculum? Does it matter which ones are emphasized? Are there particular concepts that young children are better able to understand? In another vein, what connections among these concepts should elementary students understand? How explicitly should students be able to articulate their understanding of such connections? Finally, what understanding

Table 2

Key Science Concepts

National Science Teachers Association (1964): matter, energy, change, interaction, equilibrium, entropy, transformation, time-space, motion, patterns, prediction, interdependence of living things, environment, heredity, evolution

Science Curriculum Improvement Study (Knott, Lawson, Karplus, Thier, & Montgomery (1978): interactions, systems, relativity, equilibrium, position and motion, matter, energy, ecosystem, organism, life cycles, natural selection, time-space, variables, models, property, theory.

Simpson and Anderson (1981): cause-effect, change, cycle, energy-matter, entropy, equilibrium, evolution, field, force, gradient, interaction, invariance, model, orderliness, organism, perception, probability, population, quantification replication, resonance, scale, significance, system, theory, time-space, validation.

American Association for the Advancement of Science (1989): structure and evolution of the universe, gravitation, conservation of energy, features of earth (location, motion, origin, resources) and dynamics by which its surface is changed; interaction between living organisms and earth and its atmosphere; basic concepts related to matter, energy, force, motion with emphasis on their use in models to explain diverse natural phenomena; diversity of earth's organisms--similarity in structure and function of their cells; flow of matter and energy in life cycles; dependence of species on each other and physical environment; biological evolution; human organism, population, life cycle, body structures and functions; physical and mental health, medical technologies, role of technology in shaping social behavior, political and economic organization; nature of technologies in history and today, data analysis, reasoning.

Bybee (1987): Unifying concepts for the science-technology-society theme: systems and subsystems, organization and identity, hierarchy and diversity, interaction and change, growth and cycles, patterns and processes, probability and prediction, conservation and degradation, adaptation and limitation, equilibrium and sustainability.

should students have about how these concepts developed and changed over time and how they relate to the inquiry process?

Thus, the lists of key concepts do not provide a clear picture of the kinds of understanding that are desired. If a fifth grader can say that animals need plants for food, is that evidence that she understands "interdependence of living things?" The vagueness of the expert recommendations leaves open the possibility that the curriculum will be trivialized, with teachers checking off student mastery of concepts based on quite superficial encounters with the concepts.

b. Processes. Scientists and science educators in the 1960s and 70s became very interested in the "processes" of science--the thinking processes that scientists use to do their work. During that post-Sputnik era, much effort was put into defining these science thinking processes and translating them into school curricular objectives. Although there are variations in the terms used to describe science thinking process outcomes, there has been general agreement that these thinking processes are identifiable, discrete skills that can be hierarchically arranged from concrete to abstract. Thus direct observation of phenomena is the most simple, concrete process while thinking skills such as inferring, designing experiments, and interpreting data represent the "higher level" process outcomes. Examples of how experts have organized the science thinking processes shown in Table 3 illustrate the similarities among the different experts' lists as well as the hierarchical arrangements.

While there has been significant effort put into defining these science thinking processes, there are still important unresolved issues concerning these as goals in the elementary science curriculum. For example, should these processes be taught as discrete skills in a carefully planned developmental

Table 3

Science Processes

Commission of Science Education (1970):

Primary process skills (grades K-3): observing, classifying, measuring, communicating, inferring, predicting, recognizing time-space relations, recognizing number relations

Integrated process skills (grades 4-6): formulating hypotheses, making operational decisions, controlling and manipulating variables, experimenting, interpreting data

Carin & Sund (1980):

Discovery processes: observing, classifying, measuring, communicating, inferring, experimenting

Science processes: identifying problems, observing, hypothesizing or predicting, analyzing, inferring, asking insightful questions about nature, formulating problems, designing experiments, carrying out experiments, constructing principles, laws and theories from data, extrapolating, synthesizing, evaluating

Wolfinger (1984):

communication processes
observation
using members
prediction
inference
conclusion
classification
space relations
interpreting data
formulating hypotheses
controlling variables
experimenting
cause & effect
operational questions
interaction and systems

Farmer and Farrell (1980):

Induction: observing --> gathering data --> data reducing --> extrapolating --> classifying --> experimenting --> inferring

Deduction: generalizing <--> theorizing <--> reasoning by analogy and other rules of logic sequence? Or should they be taught in a more integrated way from the very beginning? What does it mean to say that a second grader or a fifth grader understands how to observe and make inferences? How should such understanding deepen over time? How should our expectations of a student's ability to observe or infer change across the K-6 years? Are there other important processes in science that have been left off the experts' lists? What about decision making? What about using scientific knowledge to build a new machine? Are such technological thinking processes part of science? Should they be part of the elementary science curriculum? How are the thinking processes linked to scientists' conceptual knowledge, and how should that be reflected in the school curriculum?

Thus, while there has been progress in defining the science process goals, even in this area it is often unclear what is meant by "understanding." The nature and depth of desired student understanding of a process skill, such as observing, needs to be more carefully investigated.

c. Attitudes. This is the area that is the least clearly articulated in the literature. While it is easy enough to describe the attitudes and values of scientists (see Table 4), it is not so easy to translate these into K-6 curricular goals. Should these attitudes and values be explicitly taught and discussed, or will they grow out of students' participation in hands-on activities? Are all of these values able to be understood in meaningful ways by K-6 students? For example, are fifth graders better able than first graders to be skeptical and to appreciate the changing nature of science?

Clarification of the complexities of some of these attitudes is also needed. It is easy to say that young students studying science should be "questioning of all things." But don't we also want them to learn the difference between good questions and trivial ones? And we don't want them to

Table 4

Attitudes and Values of Science

Carin & Sund (1980): intense curiosity, humility, skepticism, determination, openmindedness

Educational Policies Commission of NEA (1966): longing to know and understand, questioning of all things, search for data - their meaning, demand for verification, respect for logic, consideration of premises, consideration of consequences

National Science Teachers Association (1971): perception of the cultural conditions within which science thrives, recognition of the need to view science within the broad perspectives of culture, society, and history, appreciation of universality of scientific endeavors

Simpson and Anderson (1981): science as a human activity, changing nature of science, relationships to other realms, limitations of science, science requires openness, variable positions and disagreement, social influence on science/technology, impact of science/technology, value of scientific knowledge

National Center for Improving Science Education (Bybee et al., 1989): desiring knowledge, being skeptical, relying on data, accepting ambiguity, willingness to modify explanations, cooperating in the answering of questions and solving problems, respecting reason, being honest

American Association for Advancement of Science (1989): respect for the use of evidence and logical reasoning in making arguments, honesty, curiosity, openness to new ideas, skepticism in evaluating claims and arguments; informed, balanced beliefs about social benefits of science; critical response skills to judge assertions made by advertisers, public figures, etc., and to subject their own claims to some scrutiny so as to be less bound by prejudice and rationalization.

ask questions without ever getting personally satisfying answers. Students should also develop an attitude that science can help them develop meaningful answers to their questions.

And are there other attitudes that are important for learners that are not so particular to science? For example, should attention be focused on students' attitudes towards themselves as learners? Might it be more important to help a student develop metacognitive strategies and a positive self-concept about his/her own ability to learn science (a personal relationship with science) than to focus on helping that student investigate relationships between science and society-at-large?

Thus, as with content and process goals, the experts' lists of ideal attitudes need further analysis to define which ones are most important and reasonable for elementary children to learn. If these lists of attitudes and values are going to be a meaningful part of the elementary science curriculum, a clearer picture is needed of what a child who holds these values would look like. Lists of goals have focused too much on the picture of the graduating 18-year-old.

"Do It All"?

A second issue that needs to be explored is whether these lists of goals are reasonable and helpful given the current context of elementary science instruction. As I read these sets of lofty-sounding goals, I worry about elementary teachers' reactions. It has been well documented that elementary schools teachers typically lack strong science preparation or interests (Coble & Rice, 1982; Hegelson, Blosser, & Howe, 1977; Stake & Easley, 1978; Weiss, 1978 & 1987) and that elementary science instruction is allotted a very small slice of the typical school week if it is taught at all (Fulton, Gates & Krockover, 1980; Horn & James, 1981; Sirotnik, 1983; Weiss, 1978, 1987). It seems likely that teachers who are insecure in their science background, who are faced with teaching five or more subjects to their students, and who face particular pressures to teach reading and mathematics well would be overwhelmed by the multiple goals that experts have identified for science instruction alone. It is difficult to imagine that such lists of goals would be helpful to teachers in either day-to-day or long-range planning for science. There are just too many different balls to juggle.

Achievable Goals

For the goals to be meaningfully addressed, I believe they need to be embedded in an integrated framework or model that addresses selected goals rather than in long lists that cover *all* desirable goals. The main organizing framework in current lists of goals are the content, process, and attitudes categories. This organization does not provide an integrated, workable model; instead, each category of goals is a separate piece of the science curriculum--an additional ball to juggle. The language in science methods textbooks and in NSTA's position statements communicates a similar balancing act.

NSTA (1982), for example, produced graphs showing approximate percentages of science instructional time at each grade level that should be spent on process skills, content goals, application, and science-based societal issues. In first grade the process "ball" gets the most play. By fifth grade the content ball is the biggest ball in the juggling act. The lists of ideal goals articulated by NSTA and other experts seem far removed from what is possible in most elementary classrooms. Instead, such list making about *ideal* goals should only be a first step in the development of *achievable* goals for elementary science.

A new way of defining *achievable* goals for elementary science that incorporates knowledge about how young children learn science and knowledge about instructional practices that foster meaningful understandings is needed. If we want science to be taught at the elementary level and taught so that students are developing rich and higher level understandings of science, the goals we define need to be focused and organized in ways that are useful in guiding curriculum decisions and teacher planning. Hard decisions need to be made in order to generate a realizable and clearly framed set of goals for elementary science.

A second step in the process of defining realizable goals is to articulate more clearly the kinds of scientific understanding and thinking we want students to develop. What kinds of content should students study, and what kinds of thinking should they learn to do about that content? What role should fact learning play in elementary school science learning? How much content should students study?

Each of the three perspectives reviewed in this paper makes important contributions in clarifying possible visions of how particular goals might be translated into curriculum, into instruction, and into achievable student outcomes. Each perspective also has a vision of what scientific thinking could look like in school classrooms. All three visions contrast sharply with science teaching as it is typically taught at the elementary level.

What Science is Currently Taught in Elementary Schools?
Consistency of the Enacted Curriculum

A picture of the current status of elementary instruction will serve as a point of contrast with the experts' general recommendations and with each of the three curriculum perspectives discussed in this paper. I offer this rather discouraging description of the status of elementary science instruction not to denigrate teachers but rather as a way to emphasize the need for a statement of limited but realizable goals for elementary science curriculum and instruction.

Time Allotted for Science Instruction

Many studies have found that despite differing perspectives about what should be taught in elementary science, there is in fact little science taught of any kind (Coble & Rice, 1982; Hurd, 1986; Sirotnik, 1983; Stake & Easley, 1978; Weiss, 1978). In their case studies of 11 school districts, for example, Stake and Easley (1978) found that in none of the schools was science consistently taught throughout the elementary grades. In some districts almost no science was being taught. Science received the least time of the major curriculum areas:

> Although we found a few elementary teachers with strong interest and understanding of science, the number was insufficient to suggest that even half of the nation's youngsters would have a single elementary year in which their teacher would give science a substantial share of the curriculum and do a good job teaching it. (Vol. 2, p. 13:18)

In observations of 129 elementary classes (12 schools) Sirotnik (1983) found that 2.4% of instructional time at the K-3 levels was spent on science (the lowest of all subject areas including the arts) and 12.8% of instructional time focused on science at the 4-6 grade levels (which was higher than the arts and social studies). Science was consistently found to be a poor fourth (to reading, mathematics, and social studies) in instructional time in studies by Weiss (1978), Fulton et al. (1980), and Horn & James (1981). Weiss (1987) reported no change in the average number of minutes per day spent on science between 1977 and 1987 (19 minutes at K-3; 35-38 minutes at 4-6). Typically science is taught after 1:30 p.m. and 2 or less days per week (Fulton et al., 1980).

Why so little science? There have been a number of studies that have investigated the reasons why so little science is taught. Survey data indicate that teachers avoid science teaching because of a lack of confidence in their own subject matter knowledge (Weiss, 1978), because of a lack of materials (Miller, 1986), and because of lack of training in how to teach science. Horn & James (1981) found that teachers not only feel unqualified to teach science, but many of them do not see science as important to teach. The back-to-the-basics movement fed this argument and also put demands on teachers to give reading and mathematics more instructional time. In addition, teachers report time pressures in planning for science as a reason for not teaching more science.

Content of the Elementary Science Curriculum

Stake & Easley (1978) reported that when science is taught it is typically textbook-based and characterized by teacher talk and teacher explanation. In a classroom observational study of fifth-grade science teaching, Roth, Anderson, & Smith (1987) found that the pattern of teaching in these text-based science classrooms consisted of oral reading of the text followed by answering of predominantly factual questions. Teachers posed questions and listened to student answers until right answers were given. Thus, science teaching focused on teacher/text presentation of content, and science learning was viewed as student acquisition of facts.

There is evidence that little of the three perspectives described in this paper--the inquiry approach, the science-technology-society emphasis, or the conceptual change approach--is enacted currently in elementary science teaching. Despite the large-scale curriculum development efforts in the 1960s and early 1970s funded by the National Science Foundation (NSF), which emphasized hands-on science activities and inquiry approaches to science teaching, elementary science teaching in the 1980s is largely textbook-driven (Miller, 1986). Weiss found, for example, that the three major NSF inquiry programs were, in 1976-77, the "most often used" curriculum materials in only 8% of the nation's elementary school classes. The single textbook was the program used in the majority of classrooms where science was being taught (Coble & Rice, 1982; Weiss, 1978). In 37% of K-3 classrooms and 10% of 4-6 classrooms, no text or program was reported being used (Weiss, 1978). The pattern of textbook use had not changed in a similar survey conducted in 1985-86 (Weiss, 1987).

One way to understand the substance and emphasis of the elementary science curriculum is to look at the content and instructional emphases of the most widely used science textbooks. A recent analysis of widely used science curriculum materials at the fifth-, ninth-, and twelfth-grade levels in the United States was conducted as part of the Second International Science Study (Miller, 1986). At the fifth-grade level the science textbooks most widely used in the early 1980s were characterized as emphasizing factual knowledge and content. My own review of the most widely used elementary science textbooks, as well as reviews by the National Center for Improving Science Education (Bybee et al., 1989) and by Meyer, Crummey, and Greer (1988), found a similar presentation of science as a body of facts about natural phenomena.

This factual approach to science is generally organized around discrete topics (such as fossils, plants, rocks, weather, electricity, ecology, magnets, light, etc.). At each grade level, seven to nine such topics are presented. Topics for a given grade level are selected to represent the major subdisciplines in science (earth science, life science, physical science). These topics can be taught in any order, and teachers usually select those topics that they feel best prepared to teach. In the texts there is little or no attempt to make explicit conceptual connections among the topics addressed at a given grade level. Topics are arranged in a K-6 scope based again on a "sampling of science topics" strategy: If fourth graders study simple machines and sound as their two physical science units, then fifth graders will study light and electricity.

Within each topic, or unit, the text presents information related to the topic in an "all about" fashion. These presentations of information are typically organized as a series of facts about light, weather, and so forth. Especially at the upper grade levels, these facts cover a lot of ground without exploring any idea in depth. Explanations of phenomena are presented briefly and in quick succession, as if each explanation were simple and straightforward, as if all ideas presented are of equal importance, and as if one brief reading and discussion of the explanation is adequate for students to understand. The most skilled science teachers recognize that students cannot really understand ideas presented so briefly and superficially. However, they sometimes justify covering the content in the text as a way to "expose" students to lots of different areas of scientific knowledge and do not worry about the sense students make of it: Understanding will come later on when they study this content in high school or college.

Scientific Thinking and Process Skills in the Enacted Elementary Science Curriculum

The texts (and teachers who follow the texts closely) also do little to convey the spirit of scientific inquiry and debate. These issues are typically addressed in a chapter at the beginning of each grade level text about "the" scientific method, while the bulk of the text presents scientific knowledge as facts without suggesting where these facts come from and without encouraging students to raise questions about the text's authority in making these statements.

The textbooks that are in use today incorporate more suggestions for activities than pre-Sputnik textbooks, but these activities do not emphasize the process and inquiry goals of the NSF activity-based programs. Miller (1986) notes that the activities are rarely used to develop higher order thinking skills such as analysis, evaluation, and synthesis. Instead, the opportunities for "learning by doing" focus on simple observation and measurement:

> Routine practice in techniques of science, such as weighing or measuring objects, observing artifacts via instruments were stressed above the more thoughtful, structured inquiry investigations that were at the heart of projects like SCIS or SAPA (p. 37).

In my own review of popular science textbooks and in studies of these texts in use, I have found that hands-on activities are integrated into each unit as options for teachers to use rather than as the focus of science instruction. While the rhetoric of the teacher's guides suggests that these activities develop the thinking process skills of science, the activities usually are structured in ways that focus on observation and description of phenomena that have already been described in the text. The questions asked in conjunction with these activities frequently ask for correct descriptions (of flower parts, for example) or textbook-acceptable explanations rather than eliciting students' ideas and explanations. Just as the text presents content as discrete bits of information that are not tightly linked into a conceptual framework, it also presents science activities as isolated experiences that seem to be selected because they are interesting, fun, and easy to do rather than for their usefulness in developing conceptual understanding or higher level thinking. They are always related to the topic at hand but often more as interesting sidelights rather than as tasks that are integrated into the development of student understanding of important concepts.

Thus science textbooks typically separate science into a body of knowledge about the natural world that comes from the text and into activities that supposedly address process goals but that also have textbook-given right answers. Miller concludes that the texts of the 80s have made attempts

> to include some of the flavor of inquiry programs in science curricula for the elementary grade levels, [but] it appears that entrenched, time-honored practices of learning such as textbook reading, recitation and memorization leading to basic knowledge and comprehension of science are emphasized over training students to think critically in science. (p. 38)

Higher Level Thinking and Conceptual Understanding in Enacted Elementary Science Curricula

The questions posed in science textbooks and by teachers are most often factual level questions. Only occasionally do questions require higher order analysis, explanation, or critical thinking, and these questions are typically buried at the end of chapters or units (Miller, 1986). Supplementary worksheets include a preponderance of crossword puzzles, matching activities, and word searches that engage students in reviewing facts and vocabulary. Questions that require students to develop an explanation longer than a sentence are rare. The short-answer questions do not serve to engage teacher and students in sustained dialogue about natural phenomena. Instead, teachers and students quickly go over the correct answers to these questions. Because the questions are usually answered in the text, there is little need to stop and discuss a particular question in any depth: There is one, clearly stated answer, and students' personal ways of answering some of the questions do not get noticed or examined in the search for "the" answer.

Assessment of Student Learning in Elementary Science

Most textbooks in use today include ready-made chapter and unit tests. What do these tests communicate to teachers about the goals of science instruction? What kind of learning do they assess? Not surprisingly, the tests typically assess students' recall of factual information. These questions are frequently in multiple choice, true/false, and matching formats, which are easy for teachers to score but often difficult for students to interpret so that teachers must prepare students for the test by talking about test-taking strategies as well as about science content. For example, teachers using Holt *Science* (Abruscato, Hassard, Fossaceca, & Peck, 1984) have told me how they have to spend time teaching students how to read and respond to questions like the following for fourth graders:

> Which does *not* happen to light as it travels away from its source?
> a. It spreads out.
> b. It get thinner.
> c. It gets brighter.
> d. It gets dimmer. (p. T 59e)
>
> Which sentence is true?
> a. Light particles spread apart as they move away from their source.
> b. Light particles are closer together as they move away from their source.
> c. Light waves get bigger as they travel.
> d. Light gets dimmer as light waves get bigger. (p. T 59e)
>
> Which sentence is not true?
> a. Air becomes hot as sunlight passes through it.
> b. Sunlight can pass through the earth's atmosphere.
> c. The earth's surface heats up the air above it.
> d. The energy to warm the earth's air comes from the sun. (p. T 111d)

Again, higher level questions are few and far between, and students rarely have to construct explanations or give answers of a sentence or more. The tests include questions about important concepts as well as about trivial details, so students must know *all* the content of the text and not just focus on understanding key ideas.

Many people concerned about the failures of science teaching in elementary schools point to declining test scores on the National Assessment of Educational Progress (NAEP). These tests have attempted to measure science achievement in four areas: content, inquiry, attitude, and science-technology-self. Three studies by the NAEP (1978, 1979a) and a follow-up study by the Science Assessment and Research Program (Hueftle, Rakow, & Welch, 1983) have shown small but consistent declines in science achievement in four test administrations to 9-, 13-, and 17-year-olds over the last 15 years. However, there are fewer data on these tests for the elementary students, and the declines among the elementary students are less than among the older students.

The inquiry questions on the NAEP assessments are also limited in what they tell us about students' use of science thinking process skills in meaningful contexts. The inquiry items are generally "content-free" and focus on assessing process skills in isolation from meaningful problems. Measurement and the use of graphs and tables are assessed more frequently because these skills are easily isolated from particular conceptual domains.

Research studies of student learning in classroom settings (elementary, secondary, and college) provides more disturbing findings about student learning. Studies of students' conceptions before and after instruction have shown that even when science _is_ taught, the majority of students fail to develop meaningful understandings of the central concepts being taught (Champagne, Klopfer, & Anderson, 1980; Champagne, Klopfer, Solomon, & Cahn, 1980; Clement, 1982; Eaton, Anderson, & Smith, 1984; Gunstone & White, 1981; LeBoutet-Barrell, 1976; Nussbaum & Novick, 1982b; Roth, Smith, & Anderson, 1983; Tasker, 1981; Trowbridge & McDermott, 1980). Instead, they cling to their entering misconceptions and naive theories about phenomena.

They can memorize facts, but they cannot *use* these facts to support their explanations of observed phenomena.

Summary

There is clearly little emphasis in current elementary science instruction on teaching for conceptual understanding and higher level thinking. Students are presented with science as an accumulated stack of established facts and theories. Although students sometimes do activities, these activities rarely engage them in genuine scientific thinking. Instead of raising questions and puzzling about the whys and hows of the natural world and instead of using scientific knowledge to explain phenomena, to generate predictions and hypotheses and experimental plans, to consider alternative perspectives, or to restructure personal conceptions, students look for the official right answers to their teachers' questions. Because these questions are so predominantly fact-oriented, the "scientific thinking" students have to do is to remember the facts or to look them up in the book. This is certainly not the rich view of scientific thinking that experts recommend as the intended goals of elementary science instruction. We turn now to a consideration of these experts' views about the desired outcomes of elementary science instruction.

Three Alternative Perspectives on the Elementary Science Curriculum

Science teaching has not changed much in the last 40 years; it was, and is basically fact-oriented and didactic. Scientists, science educators, and educational researchers have never been satisfied with the status of science education in public schools, so there have been a series of attempts to change the nature of elementary science teaching. By far the most serious and best supported of these attempts was the inquiry movement, which was dominant among reformers during the 1960s and 1970s and which gave rise to several National

Science Foundation K-6 curricular programs, extensive programs of inservice education, and the dominant perspective in preservice teacher education programs. By the 1980s, though, it was becoming 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.

Thus in the 1980s the reform movement split into three groups: (a) a still-powerful group that continues to advocate and fine tune inquiry teaching, (b) a science-technology-society (STS) group that focuses on changing the goals of science teaching, and (c) a conceptual change group that focuses on changing the methods of instruction. All three groups agree about the need for reform, but they differ in their analyses of the reasons for the failure of the 1960s reforms and in their prescriptions as to what should be done now. In the next three sections, I analyze the ways in which each perspective views the nature of scientific thinking and translates that view into goals for elementary science. Strengths and weaknesses in terms of the potential of each model to help students develop conceptual understanding and higher order thinking will be described. Following the descriptions of all three perspectives, I consider examples of how each perspective might be enacted (both in terms of content selection and instructional methods) in teaching fifth graders about plants and photosynthesis.

The Inquiry Perspective:
An Emphasis on Scientific Thinking Processes

Desired outcomes and purposes. Many science educators, science teachers, and scientists advocate an emphasis on science thinking process outcomes. They contend 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. In this view students become little scientists who explore phenomena through hands-on activities and who use and develop scientific thinking skills to build conceptual understandings gradually in the same way that scientists use experimental work to construct new knowledge, concepts, and theories.

In this inquiry approach, it is not important that students be exposed to a broad range of scientific facts and concepts. In fact, advocates of this perspective deplore the typical content focus of traditional science textbooks. They argue that traditional science curricula overemphasize science as a body of knowledge and overload students with long lists of facts and vocabulary. This gives students a distorted view of the nature of science, and it encourages students to view learning in science as a meaningless process of memorizing facts and terms. From the inquiry perspective, student investigations of phenomena (and not textbooks) should be the backbone of the elementary science curriculum, and the most important focus in those investigations should be on the use and development of science inquiry or process thinking skills--predicting, hypothesizing, observing, recording data, making inferences and generalizations, etc.

The emphasis on inquiry and process outcomes is claimed to contribute to several different overall purposes of elementary science teaching:

a. *Development of future scientists.* First, it is a way to develop future scientists. Helping students understand what scientists' work is like and involving students in doing that kind of work is a way of introducing science that will interest potential scientists to develop their interests and understanding of science.

b. *Development of transferable thinking skills.* But the emphasis on process skills is not just important for future scientists. A second overall purpose of the science inquiry approach is the development of critical thinking and problem-solving skills that students can use in all aspects of their lives. Science teaching is important as one vehicle for helping students develop such "generic" thinking skills. Proponents of this view (Carin & Sund, 1980; Gagné, 1965;

Jacobson & Bergman, 1980; Kessen, 1970; Lawson, 1985; Renner, Stafford, & Ragan, 1973; Trojcak, 1979) see inquiry science teaching as a way to help students learn thinking skills that will later transfer to everyday decision making and problem solving. The notions of objectivity, logic, and controlled experimentation developed in science will be internalized, and students will use these kinds of thinking skills in their adult lives in making decisions about which car to buy, in trying to figure how to fix a clogged garbage disposal, in analyzing political situations and making voter decisions, in figuring out how to wire stereo and TV equipment, in deciding whether or not to switch jobs, etc.

c. *Preparations for future science study*. In this view, development of science process skills in the elementary school is important as a foundation for future science study (at the high school or college level) that will be more focused on science concepts and theories. Young children are not ready to understand science concepts and theories in a meaningful way. Piagetian research suggests, for example, that elementary children are at the stage of concrete operations and are not yet capable of abstract thinking and formal reasoning. Therefore, the emphasis should be on developing process thinking skills to help move students toward formal reasoning and to develop science thinking skills that can later be used to study in a meaningful way accepted science concepts and theories.

d. *Development of positive attitudes toward science*. Proponents of the inquiry perspective believe that the emphasis on science processes and doing science will help develop future citizens who value science and who are not fearful of science and scientists. By becoming little scientists, students learn to understand science as a human endeavor, and their curiosity and wonder are stimulated. Rutherford (1988) describes this purpose as helping students become "comfortable in the neighborhood of science".

Historical and theoretical background. The inquiry perspective has its origins in societal and political developments, arising largely as a response to political events and concerns. Although advocates of process-oriented approaches to science teaching existed before the launching of Sputnik by the Russians in 1957, science teaching from 1920-1950 was predominantly textbook-focused. Educators attempted to keep up with rapid changes in science and industry by presenting important ideas to students in sequenced textbooks. The launching of Sputnik, however, created a national paranoia that the United

States was falling behind the Russians in science and technology. Science education needed to be improved quickly to develop a pool of future scientists that would enable us to remain scientifically and technologically competitive with the Russians.

In response to this concern, The National Science Foundation poured money into national science curriculum development efforts. These curricula were written by teams of scientists, psychologists, and educators. There was a focus on tapping the best thinking of these various experts to develop curricula that more accurately reflected the nature and structure of the science disciplines. Influenced by Bruner's notion (1963) that any idea can be taught to students at any level in an intellectually honest way and Piaget's notions (1929/1969) that children go through stages in the development of their cognitive abilities, these curriculum development teams constructed curricula that would engage students in acting as scientists in ways appropriate for their level of cognitive development. The three most widely implemented elementary curricula were Science--A Process Approach [SAPA] (American Association for the Advancement of Science, 1970), Elementary Science Study [ESS] (Education Development Center, 1970), and the Science Curriculum Improvement Study [SCIS] (Science Curriculum Improvement Study, 1970).

While these three curricula represent important differences in the ways in which content and process are related, they share a Piagetian framework for thinking about children's learning of science. This is reflected in their strong emphasis on learning by doing and on involving students actively in the learning process. The physical manipulation of materials was viewed as a critical part of this learning process, and Piagetian ideas about developmental stages were used to make decisions about the kinds of activities, processes, and content that would be appropriate for a given grade level. The "doing" activities involved students in what was termed inquiry or discovery learning. Students could explore events and phenomena firsthand and develop from those observations important concepts and generalizations. A popular slogan for this active work was, "I do and I understand".

These curriculum materials and second generation versions of them were implemented and studied during the 1960s and 70s, with substantial support from the National Science Foundation. In the 1980s they have all but disappeared from elementary classrooms, but the need for hands-on activities and the development of process skills continues to be emphasized by many science teaching experts. Lawson, Abraham, & Renner (1989) for example, continue to revise, develop, and study activities in the SCIS curriculum materials. It is almost a commonplace among science teachers, science educators, and scientists today that elementary science teaching should involve many hands-on activities (American Association for the Advancement of Science, 1989; Carin & Sund, 1980; Esler & Esler, 1981; National Assessment of Educational Progress, 1979; NSTA, 1982; Renner, Stafford, & Ragan, 1973; Rowe, 1978; Trojcak, 1979).

Relationships among content, thinking processes, and attitudes. The proponents of an inquiry orientation to elementary science teaching acknowledge that science content and science thinking processes are both important parts of science and that they are clearly interrelated. However, they place a clear emphasis on science thinking process skills, allowing science content (facts, concepts, generalization, theories) to play a secondary role.

Within this inquiry perspective, there is a range of viewpoints about the role of content in process-focused teaching. At one end of the continuum, 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. This view of content is best represented in the Elementary Science Study curriculum materials. The ESS group did not construct a curriculum around a particular conceptual scheme. Instead, they "relied upon taking what we thought were good scientific activities into classrooms to see how they worked with children. We have tried to find out what . . . six-year-olds, and nine- and thirteen-year-olds find interesting to explore" (Educational Development Center, cited in Renner, Stafford, & Ragan, 1973, p. 269). The ESS curriculum consists of 56 units that can be taught in any order, with each unit being appropriate for students at several different grade levels. The units consist of classroom activities and materials that teachers can use to involve students in the processes of science. Units include butterflies, mobiles, brine shrimp, clay boats, ice cubes, batteries and bulbs, optics, small things, behavior of mealworms, starting from seeds. Hawkins (1965), an ESS director, emphasized the importance of allowing children to "mess about" freely in science. In his view, children should be allowed significant time to explore science materials and equipment without directed questions as instructions.

In the mealworms unit, for example, students (grades 4-7) observe an unfamiliar animal, ask questions about the animal's observable behavior, and design ways to answer their own questions:

> As children observe and experiment, they learn some things about the process of scientific inquiry while they gather information about the sensory perception of the mealworm. The primary objective of the unit is to help children learn how to carry out an investigation. (Renner, Stafford, & Ragan, 1973, p. 273).

In this unit, mealworms are a convenient way to involve students in biological investigation. The content learned about mealworm behavior is not the central goal of the instruction and will most likely be unrelated to the content of other units studied across a given school year. Once the mealworm unit is completed, for example, students may begin the unit on batteries and bulbs. The connections between the units are the scientific thinking processes. Conceptual links between units are not part of the design.

Rutherford recently described a similar view of the elementary science curriculum. His notion of helping students feel comfortable in the neighborhood of science shares Hawkins' notion of "messing about" in science:

> Science is active. It's pushing and pulling, counting, measuring, proposing, testing. That's what science is; science learning must be the same. Science is making up stories. . . It's inventing answers to the questions we make up. So kids should have experience making up stories about the things they encounter that they think could make some sense out of this experience. The insights will grow and mature over time and erratically and we shouldn't worry about that. It simply doesn't matter that they get some things wrong along the way, that their explanations aren't correct. There's plenty of time in spite of all the worry these days about people who have incorrect notions. There's a group of cognitive scientists these days, who worry about misconceptions. I worry a lot less about that among young people than most of us. Just remember, most of what we know about things other than what we earn our living doing, is very fragmented, very incomplete, and a large fraction of it is always wrong. We need to make students feel comfortable with the things, ideas and processes of science. Just as we want them to feel comfortable and accepted in their own neighborhood. They need to develop confidence that they can ask questions, that they can learn. (Rutherford, 1986, p. 7)

In the SAPA curriculum materials, content is also of secondary importance, but the units are more explicitly organized around conceptual as well as process goals. The K-6 SAPA curriculum is structured around 13 process skills that were identified by a task analysis of research scientists' work (Commission on Science Education, 1970). Content was selected that would serve as a vehicle for helping children develop facility with those 13 thinking processes. The content was limited to 5 physical science concepts (solids and liquids, gases, changes in properties, temperature and heat, force and motion) and 5 biological science concepts (observing and describing living things, animal behavior, human behavior and physiology, microbiology, and seeds and plant growth). Each of the content topics is treated at several grade levels in the SAPA program. The SAPA developers describe the secondary importance of content in this program:

> Certainly you cannot teach scientific processes without using some content. Much science content is included in Science--A Process Approach, but the emphasis is on the processes. In order to attain competence in the processes of science, children deal with such topics as plants, animals, energy, light. . . . The children become very interested in and curious about the topic they are studying even though the primary objective of instruction is for them to acquire new competencies in the processes of science. (Commission on Science Education, 1970, p. 11).

The SCIS curriculum represents the other end of the continuum. In this program there is an attempt by the developers to integrate content and process (Knott et al., 1978). The activity-focused units are organized around key concepts that are central to the structure of the biological and physical sciences. Through sets of activities, these concepts are developed and built upon within a given grade level as well as across grade levels. The total curriculum is organized around 4 scientific concepts (matter, energy, organisms, and ecosystem) and 5 process-oriented concepts (property, variable, system, reference object, scientific theory).

In all units students participate in firsthand investigations designed to lead to the development of understandings of particular scientific or process-related concepts. In the fifth grade, for example, students observe plant growth in varying conditions in order to develop ideas about how plants get their food. The program is not intended to be a pure discovery (inductivist) approach, however. At a key point in instruction the teacher explains key concepts, such as photosynthesis, which students are encouraged to use in explaining their firsthand observations. Thus, while the SCIS curriculum is structured around hands-on activities designed to involve students in the processes of science, it is also structured around key concepts in science.

Unlike ESS and SAPA, the development of increasingly complex understanding of these concepts is an explicit purpose of the investigations.

Conceptual understanding and higher level thinking. In the development of the NSF-funded curriculum development projects, there was a careful analysis of the nature of scientists' thinking. This analysis was used to define the kinds of scientific thinking that should be the desired outcomes of elementary science inquiry programs. Most of this analysis focused on what is referred to as scientific processes--the thinking processes that research scientists use as they seek answers to questions and develop new knowledge and explanations of natural phenomena.

From an inquiry perspective, the science process thinking skills are generally regarded as being at the heart of scientific thinking, and these are typically organized in a hierarchical fashion. For example, SAPA developers (Commission on Science Education, 1970; Gagné, 1965) identified 13 science processes and organized them in a hierarchy related to students' cognitive development. Certain processes were identified as being particularly appropriate to teach students in the primary grades: observing, classifying, measuring, using time-space relationships, communicating, predicting, inferring, and using numbers. Integrated process skills were deemed appropriate for the intermediate grades: formulating hypotheses, controlling variables, interpreting data, defining operationally, experimenting. Within each of the 13 processes, a developmental sequence was described. For example, in developing the ability to formulate hypotheses students would first learn to distinguish hypotheses from inferences, observations, and predictions. Later, students would learn to construct hypotheses and to demonstrate tests of hypotheses. Wolfinger (1984) extended this list and the levels within each and then matched that list with quite specific recommendations about which processes can be taught effectively at different grade levels. Peterson, Bowyer, Butts, and Bybee (1984) define 10 science processes and suggest that the first 4 can be learned by children in K-4 (observing, comparing, measuring, and classifying) while the next four can be developed during intermediate grades (gathering and organizing information, constructing and interpreting graphs, inferring and predicting). [Two process skills are associated with abstract thought or reasoning and can begin to develop in grades 6-8 (forming hypotheses and describing relationships)].

Thus, process skills are often equated with and represented as the scientific thinking skills, and they are defined and organized into a developmental hierarchy. For each process skill there is a hierarchy of children's developing abilities. Piagetian influence has played an important role in constructing these hierarchies based on students' readiness levels.

While scientific thinking skills are often presented in a developmental hierarchy, they are also organized in a hierarchy reflecting the sequential steps in inductive models of scientific reasoning. The steps in this "scientific method" include: observation, gathering of data, data reduction, extrapolation, classification, experimentation, inference (Farmer & Farrell, 1980). Some experts also articulate deductive science processes such as generalizing, theorizing, and reasoning by analogy or rules of logic (Farmer & Farrell, 1980), although these processes are more rarely incorporated into teaching materials.

What is striking in the inquiry-oriented literature on higher level thinking skills in science is the careful attention paid to describing, organizing, and sequencing the science thinking process skills and the relative lack of attention to the use of these thinking processes in a conceptual context. For example, little attention is given in these analyses to the nature and development of scientific conceptual understanding. There seems to be an assumption that scientists' development of conceptual knowledge is a fairly straightforward process that does not require serious analysis. The literature does attempt to describe the central science concepts that scientists share and that are important to teach (see Table 2), but there is little attempt to articulate the kinds of *thinking* it takes to develop such conceptual understandings or to explore the relationships and distinctions between understanding science processes and understanding science concepts. For example, there is little attention to the ways in which a particular conceptual framework can drive the questions one asks and the aspects of an experiment that one "observes." Instead, the relationship between conceptual knowledge and scientific processes is described in a one-way fashion, suggesting that conceptual knowledge is simply the "product", or outgrowth, of the scientific thinking processes. Thus, there is an emphasis on identifying the *content* of scientists' conceptual knowledge (*what* they know and how they organize that knowledge) without an equal emphasis on analyzing the kinds of thinking needed to develop, organize, and use that knowledge.

Not only is science process thinking sometimes envisioned and taught in relative isolation from conceptual development. In some inquiry curricula, thinking skills (processes) are also taught in relative isolation from each other. Thus, a student may be taught to observe carefully in isolation from problem setting, predicting, and other process skills. For example, children may be asked to describe as many details as possible about a phenomenon. The goal is to give detailed observations, not to develop better understandings of the phenomenon being observed. While scientists rarely observe without some guiding questions and frameworks, students are sometimes taught to observe for practice in careful observation.

The inquiry perspective as enacted in the NSF curricula of the 1960s and 1970s uses the discipline-bound research scientist as its model of scientific thinking. The thinking process emphasized are those involved in constructing knowledge about natural phenomena from experimental work (What does this experiment suggest about plants' need for water?) The thinking processes involved in using scientific knowledge to solve everyday problems, to make societal decisions, and to understand the limits and possibilities of technology were not central in their model of the expert scientific thinker. As a result, the NSF-funded curricula do not emphasize the links between scientific knowledge/processes and personal/societal problems. In SCIS, for example, the emphasis is on using experimental evidence to construct explanations about important disciplinary ideas such as energy and photosynthesis. There is little emphasis on using such explanations to make better sense of students' questions and experiences in the world: Could we live without sunlight? Couldn't we just use electric lights? If the plants died, couldn't we just live on candy bars? There was also minimal attention to societal problems and decision making (How can we conserve energy resources?) or to the role of technology in solving societal problems.

Figure 1 is a simplified, schematic representation of the relationship among content, process, and attitudes in an inquiry-oriented curriculum. It highlights the prominence of science process skills as 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 generally viewed as outgrowths, or products, of students' inquiry-oriented investigations. The focus of instruction is on a hierarchy of process skills. If students can understand and use these general thinking process skills, they

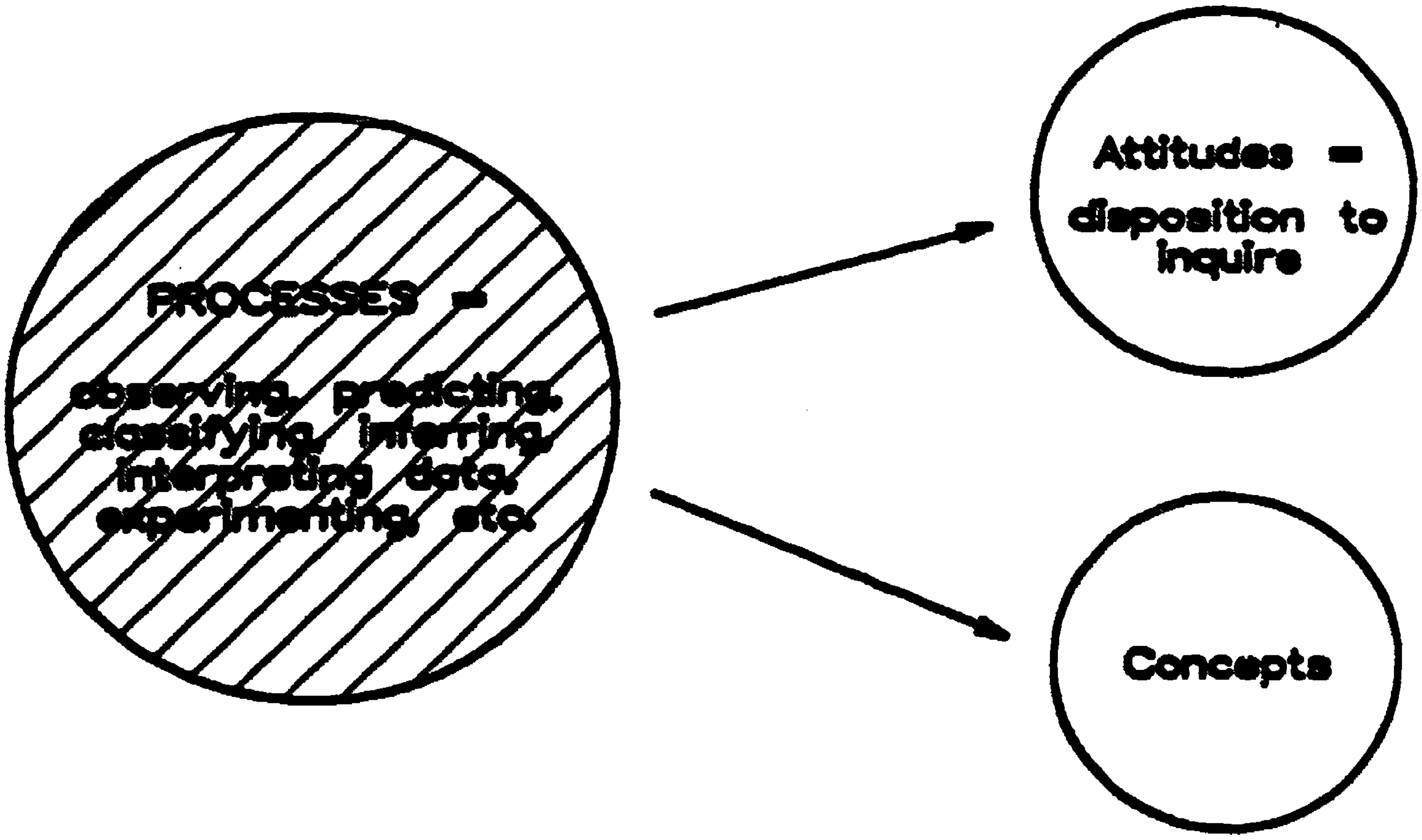

Figure 1. Relationships among science concepts, processes, and attitudes in an inquiry perspective. Shaded areas indicate higher level thinking.

will be able to develop meaningful conceptual understandings in any area of study.

Assessments of inquiry teaching and learning. Of the three perspectives presented in this paper, the inquiry perspective has been the most widely implemented and the most thoroughly evaluated. In fact, the National Science Foundation funded several efforts to study and synthesize the findings of hundreds of studies investigating the effectiveness of the inquiry curriculum development projects (Bredderman, 1983; Harms, 1981; Stake and Easley, 1978). There are four findings from studies of the inquiry programs that are important to consider in thinking about feasible goals and purposes of elementary science teaching:

1. First, teachers had a difficult time implementing inquiry, activity-based teaching approaches. Planning and classroom management became much more complex when students were frequently using hands-on materials in science. Since most elementary teachers are also responsible for instruction in reading, writing, language arts, mathematics, and social studies, the planning demands for just the procedural parts of lessons were a burden. These practical and time considerations were believed to be largely responsible for the lack of widespread use of the NSF programs (Stake & Easley, 1978).

2. Many teachers also lacked adequate science knowledge to lead discussions of activities that went beyond having students report results and tell their own stories to explain them. Some teachers resolved this dilemma by focusing primarily on the doing of activities, eliminating discussions of the meaning of the activities (Smith & Sendelbach, 1982). Other teachers had or developed adequate science knowledge but interpreted the discovery orientation to mean that the teacher should never tell students "answers" (Roth, 1984; Smith & Anderson, 1984). They held discussions in which students contributed

varying explanations of experimental observations, and each student's perspective, or "story," was valued and treated as a reasonable explanation. But students were not helped to reconcile their stories with accepted scientific explanations. Instead, the important thing was to create a story or explanation, and each person's explanation was equally valid.

3. Learning outcomes were not dramatic. Studies demonstrated that inquiry programs generally had a positive effect on students' development of process skills (Bowyer & Linn, 1978; Bredderman, 1983; Shymansky, Kyle, & Alport, 1983). The programs seemed to be particularly effective for disadvantaged students. However, the differences between control and experimental groups were not dramatic. In addition many of the studies of the NSF programs are open to criticism concerning the extent to which the process tests "were content-free and independent of the context in which the material was originally presented to the students" (Millar & Driver, 1987, p. 55). Finally, analysis of students' conceptual development revealed that students had similar problems to students in textbook-centered, didactic classrooms (Roth, Anderson, & Smith, 1987).

Roth, Smith, and Anderson (1983) observed students during a six-week activity-based unit about plants as producers from the SCIIS curriculum (Knott et al., 1978). They administered pre- and posttests and conducted clinical interviews to assess students' conceptual understanding, and 93% of the students in the study failed to develop 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 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 <u>many</u> sources of food for plants, failing to understand the <u>unique</u> ability of green plants to use light energy to convert nonenergy-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.

4. Much work has been done to devise assessment strategies that can be widely used to measure achievement of inquiry skills. Often these assessments involve hands-on work and analysis (Assessment of Performance Unit, 1983-87; Mullis, 1987; Mullis & Jenkins, 1988; National Assessment of Education Progress, 1987). The 1987 NAEP pilot tests of such hands-on items revealed that 3rd, 7th, and 11th grade students were relatively successful at classifying and sorting birds, seeds, and vertebrae. They were less successful at drawing inferences from observations. Students tended simply to describe observations rather than to make inferences and identify relationships.

For example, they observed a whirlybird apparatus that was used to show that placing weights from the center of the rotating arm will decrease the speed of the arm. They did not generally talk about the relationship between the placement of the weights and the speed of the arm unless prompted to do so by the test administrator. In another set of tasks students were asked to conduct experiments to find out if sugar cubes dissolve faster than loose sugar or to determine how length and widths of pegboards influenced pendulum swings. Students were generally not successful at conducting these experiments and manipulating variables.

While these assessment strategies represent an interesting attempt to assess "higher level" thinking, they are limited by their efforts to assess these skills in the absence of any conceptual context and as isolated skills (Carrick, 1987; Millar & Driver, 1987). In fact, as Millar and Driver argue, students' conceptual knowledge should have a significant effect on how they performed on so-called "process" items:

> it is clear that the choice of content and context will greatly influence the pupils' score. We must then ask: in what sense can we claim it is the 'process' that we are assessing in any science-based examination designed to assess process? (p. 54).

The Roth, Smith, and Anderson (1983) study, on the other hand, assessed scientific thinking, conceptual understandings, and understandings of the nature of science in the context of a unit of hands-on instruction about food for plants. Students in this study failed to develop meaningful understandings of science concepts about plants despite weeks of experimenting, graphing and discussing. Many of the students in this study 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 <u>why</u> 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" (Roth, in press-b).

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."

Rachel's teacher accepted everybody's "stories" and explanations as equally valid, and this also communicated a misleading picture of science to Rachel. She heard her classmates give many different explanations about why plants need light without any discussion of which explanations make more sense based on the observations. She may well have left this unit with the view that the important thing in science is to come up with an explanation. The nature and quality of the explanation does not really matter. Again, is Rachel really learning about the "processes" of science if she has learned that any explanation of observed phenomena is alright as long as it makes sense to the creator?

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?

The Science-Technology-Society Perspective: An Emphasis on Attitudes and Decision-Making

Desired outcomes and purposes. Many science educators advocate a dramatic change in desired outcomes 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.). This view is emphasized in the National Science Teachers Association position statement for the 1980s (NSTA, 1982):

> The goal of science education during the 1980s is to develop scientifically literate individuals who understand how science, technology, and society influence one another and who are able to use this knowledge in their everyday decision-making. (p. 2)

Yager and Hofstein (1986) describe this perspective in sharp contrast with both the disciplinary-based content focus of traditional science teaching and with the inquiry approach that emphasizes the development of understanding of the science processes that are used by scientists in constructing new knowledge:

> 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 (p. 134).

Yager and Hofstein drew from an NSTA study (Yager, 1980), the NSF status studies (Helgeson, Blosser, & Howe, 1977; Stake & Easley, 1978; Weiss, 1978), and the Project Synthesis analysis (Harms & Kahl, 1981; Harms & Yager, 1981) to suggest six essential goals of a quality K-12 science curriculum. These goals and the curriculum they suggest stand in striking contrast with those espoused by advocates of the inquiry perspective:

1. The human being, human potential, human advances, and human adaptations will serve as the organizer for the curriculum (instead of the structure of the disciplines or the nature of 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. Career 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, a science-technology-society 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 <u>using</u> scientific and technological knowledge to solve problems and make decisions (so that students act as young science citizens) rather than on <u>creating</u> scientific knowledge (with students acting as young scientists).

<u>Historical and theoretical background</u>. Like the inquiry perspective, the science-technology-society (STS) perspective developed largely in reaction to a social and political environment, and it has been initiated by groups of experts getting their heads together and coming up with recommendations. In the 1970s concerns about the "space race" had waned, and the civil rights movement focused educators' attention on issues of equity. In a back-to-the-basics climate, science education was not a national priority, especially at the

elementary level. Educational efforts focused instead on raising all students' reading and mathematics achievement. Beginning in 1976, NSF tapered off its funding of school science curriculum development and inservice teacher education and made drastic cuts in their support of science education research.

It was in this social and political climate that science educators in the late 1970s began to reassess lessons learned from the inquiry movement and to define new goals for the 1980s. Both the NSTA and the NSF-funded Project Synthesis sought broad input in analyzing the inquiry movement and in deliberating about new, broadened science-technology-society goals and purposes. The inquiry movement was criticized for its narrow vision of science and of science learning. The NSTA analysis (Yager, 1980) raised questions about many of the assumptions of inquiry science education. In particular, the inquiry approach was viewed as too elitist (Fensham, 1986-87) in its focus on having all learners understand the major ideas and processes that professional scientists know and use.[2] Critics agreed that the average, nonscience career-bound students might find other views of science more meaningful and useful. Thus, a more human, issues-focused curriculum would better address the needs of all students (not just those bound for careers in science).

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[2] This criticism of elitism in the inquiry-oriented science curricula was not supported by the research on student outcomes at the elementary level. In a synthesis of approximately 100 research studies, Bredderman (1979) concluded that the positive effects of the NSF-funded inquiry programs were larger for disadvantaged students than for students from average and above average socioeconomic backgrounds. Studies demonstrated that activity-based science programs contributed to low SES students' oral language development (Bethel, 1974; Huff & Languis, 1973; Rowe, 1968), to reading readiness (Ayers & Mason, 1969; Lawson, Nordland, & Kahle, 1975; Morgan, Rachelson, & Lloyd, 1977; Renner, 1973), and to low SES students' gains in certain science process skills and reasoning ability (Ayers & Ayers, 1973; Bowyer & Linn, 1978; Linn & Peterson, 1973; Linn & Thier, 1975).

The rapid changes in technology and the impact of these changes on society during this period also had a profound influence on the thinking of these experts. They saw the need to help students learn how to adapt to technological change, and they recognized that traditional science curricula are too discipline-bound to address this need. While technological advances, especially the personal computer, led many to promote the use of new technology in improving *methods* of science instruction (Linn, 1988; Linn & Songer, 1988; Tinker, 1987), the STS advocates urged a reconceptualization of the *curriculum* itself. The science curriculum should teach students *about* technology and its relationships to science (Bybee, 1987; Bybee et al., 1989).

Relationships among content, process, and attitudes. The STS perspective shares with many of the inquiry programs a relative lack of emphasis on content and the nature of conceptual understanding in organizing the school science. Like the developers of the ESS materials, STS advocates argue that content should be selected based on its interest, appeal, and relevance for students (for example, local issues and controversies are preferred over national issues). A unique piece that characterizes the STS approach is that content selection should also be based 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 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 defined quite differently from the skills emphasized in inquiry programs (which are largely limited to skills that scientists use in generating new knowledge). The processes emphasized in the STS perspective focus on wise *use* of scientific knowledge in decision making and problem solving rather than on the construction of scientific knowledge through careful observation, inferencing, etc.

In the STS perspective attitudes, values, and morals are much more closely linked to these process skills than in the inquiry perspective. Attitudes in this approach are not just a desired by-product of students' successful engagement in problem-solving activities (although advocates do claim that active involvement in exploring these issues will foster positive citizen attitudes, enabling students to feel they have a stake in societal solutions and actions). Rather, attitudes play a role in the decision-making process itself and are actively used in the thinking and problem-solving process. Students are taught how to consider values and ethics in the decision-making process.

Yager and Hofstein (1986) list five critical features of the problems or issues that are selected for use: (a) they should be transdisciplinary and emphasize decision-making skills, (b) they should connect with current issues or concerns, (c) they should have local relevance whenever possible, (d) they should include moral and ethical dimensions, and (e) the teacher should create issues or at least be able to select the most relevant issues for his/her students. Yager and Hofstein identified the following topics as potentially rich in powerful STS issues: use of energy in homes, for transportation, and for recreation; planning for proper food use and preparation; care and maintenance of the body; stress and mental health; life style and its effects on others; pollution rights and responsibilities; disease prevention and cure. A series of surveys of scientists and science education experts conducted by Bybee (1987) generated the following list of appropriate problems: air quality and atmosphere, world hunger and food resources, war technology, population growth, water resources, energy shortages, hazardous substances, human health and disease, land use, nuclear reactors, extinction of plants and animals, mineral resources.

Unlike the inquiry movement of the 1960s, the STS perspective has not been extensively supported by federally funded curriculum development efforts. As a result, there is a much less clear picture of how this perspective might be translated into day-to-day science teaching. Sample units have been suggested and field tested (especially at the secondary level), but attempts to construct an outline or framework for an entire K-6 STS curriculum are now only in the development stages (Biological Sciences Curriculum Study, 1988). However, examples of existing curriculum development efforts will be used to illustrate the relationships among science content, process, and attitudes and the nature of these components in the STS perspective.

Bybee, Peterson, Bowyer, and Butts (1984) developed a sourcebook of science and society activities for elementary students. One activity they describe as appropriate for grades 3-5 focuses on the question: What can be done to conserve plant and animal life? Although science concepts relevant to this activity are clearly identified in the teacher's guide, the suggested activities focus on students' brainstorming of ideas about ways to conserve plants and animals locally, in the United States, and in the world. Students engage in debates and decision making about the proposed alternatives; they then work in action groups to put some of these ideas into effect. How the teacher might relate these activities to the identified science concepts (native plant and animal species, the effects of humans in killing or displacing species, and the conservation of matter and energy when species are forced to change beyond their limits) is not specified. Thus, the teacher's guide emphasizes decision-making processes and attitudes over content and conceptual development.

A unit for secondary Israeli students developed by Yager and Hofstein (1986) integrates content more closely into the problem. In this unit students study three case studies of the chemical industry and then explore ecological problems faced by a local chemical industry. In the course of these investigations students study how bromine and bromine compounds are extracted from the Dead Sea and used as pesticides in agriculture and as additives in gasoline. The chemical processes of extraction and oxidation-reduction are studied along with ecological concepts related to the use of pesticides and fertilizers. Students use this knowledge in a decision-making simulation process to decide on a location for a new factory that produces bromine and bromine compounds. In this decision-making process students must consider their values and ethics as well as their knowledge about the relevant science, technology, and society concepts.

Yager and Hofstein point to the problem-solving activities built into the Unified Science and Mathematics for Elementary Schools Curriculum [USMES] (Shann, 1977) as another model for appropriate elementary level STS units. The USMES units engage students in long-term investigations of real and practical problems taken from their school or community environment. The units fit the STS emphasis on development of problem-solving skills and the call for interdisciplinary, locally relevant issues. Examples of USMES problems (called "challenges") include:

- Pedestrian Crossings--to recommend and implement changes to improve the safety and convenience of a pedestrian crossing near the school
- Soft Drink Design--to produce a popular new soft drink at a low cost
- Burglar Alarm Design--to build a burglar alarm which will give adequate warning to a specified area
- Weather Prediction--to determine what information is most helpful for accurate weather predictions.

In an evaluation of the USMES program, Shann (1977) found that science content received little attention in the implementation of USMES. Teachers viewed most of the units as teaching the scientific method but not the content of science.

In the new Biological Sciences Curriculum Study K-6 materials (BSCS, 1989), health is used as the central science and society issue. Bybee and Landes (1988) argue that the societal issues relevant to elementary students (in _their_ society) center around health concerns. Thus, each grade level in the BSCS curriculum is organized around three conceptually linked units--one focussing on science, one on technology, and one on health.

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

Like advocates of the inquiry perspective, STS proponents view active involvement in activities as the way to develop these higher level thinking skills. However, STS activities differ from inquiry activities in their emphasis on decision making and problem solving. The key is to identify an appropriate problem for investigation that will capture students' interest. As in the inquiry perspective, the particular content or concepts being taught are of secondary importance to the decision-making process itself. There is also a similar and striking lack of analysis in the STS literature about the ways in which students will develop knowledge about the particular content or concepts needed to make good decisions or to solve problems. 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 solve problems) is straightforward information that *all* students (and not just the elite future scientists) will rather easily incorporate into their 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 (see Figure 2).

An important aspect of higher level thinking that has not been seriously tackled by STS proponents is the nature of technological thinking. As Black (1987) notes, technology goals are often added to science goals as if they were merely an extension of science: "'and technology' trips off the tongue, whereas I think the distinction between the two, if we are orienting ourselves towards a curriculum for preparing citizens for the future, is quite vital and must be conceptually clarified." (pp. 19-20). Black provides one analysis of the differences between scientific and technological thinking and the implications of those differences for school science. He emphasizes that both scientific thinking and technological thinking involve a complex integration of concepts and processes. However, the nature of those concepts and processes are different in scientific and technological thinking. These differences need to be understood and considered in constructing good science and technology school tasks.

For example, in a school *science* task children may be given different kinds of blocks and asked to compare the blocks and to find out why the blocks float in different ways. Their task is to find out *why*, to propose and test a model to explain a phenomena. A *technological* school task, in contrast, might involve students in constructing a model turbine engine. Here the purpose is

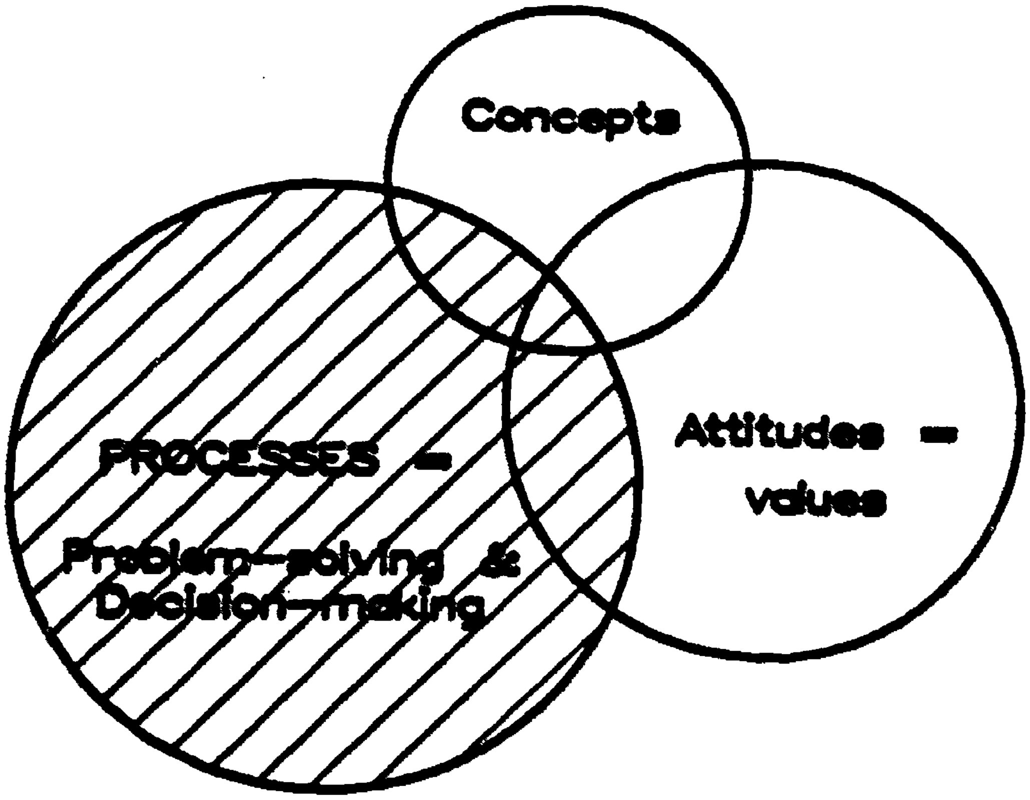

Figure 2. Relationships among science concepts, processes, and attitudes in a science—technology—society perspective. Shaded areas indicate higher level thinking.

to find a solution to a problem. To solve the problem, children must draw from relevant concepts to take action, make decisions, and produce a final product. Black asserts that while this example does illustrate key features of technological thinking, it is not a particularly good school task for developing technological thinking because it is not intimately related to human needs and values. "Who wants a steam turbine? What human purpose does it serve?", he asks. A full definition of technological thinking in his view should include perception and understanding of human needs and value judgment about who denies those needs and how decisions are made about whether a particular solution is better or worse for society than another.

The National Center for Improving Science Education (Bybee et al., 1989) has developed a model to clarify relationships between science and technology and the implications of these relationships for education goals (see Figure 3). They describe science as seeking explanations to questions about the natural world and technology as proposing solutions to human problems of adaptation. Technology is misrepresented, they assert, when it is defined simply as "applied science." As the Center authors explain, the methods of scientific inquiry and technologic problem-solving share many common elements, but "the latter are distinguished by a concentration on decision-making and risk-benefit analysis" (p. 14). The report authors attempt to detail some of the complexities of such technological thinking:

> There are many possible solutions to problems in human adaptation, and inevitably there also are many objectives and requirements. Some of these are constraints, such as availability of materials, properties of materials, laws of thermodynamics, and societal requirements. Other variables are cost and performance criteria (Caplon, 1988). Engineers often complete several designs for projects so that they can assess trade-offs among constraints and variables before making decisions.
>
> Although the methods of scientific inquiry and technologic problem-solving have many common elements, the latter are distinguished by a concentration on decision-making and risk-benefit

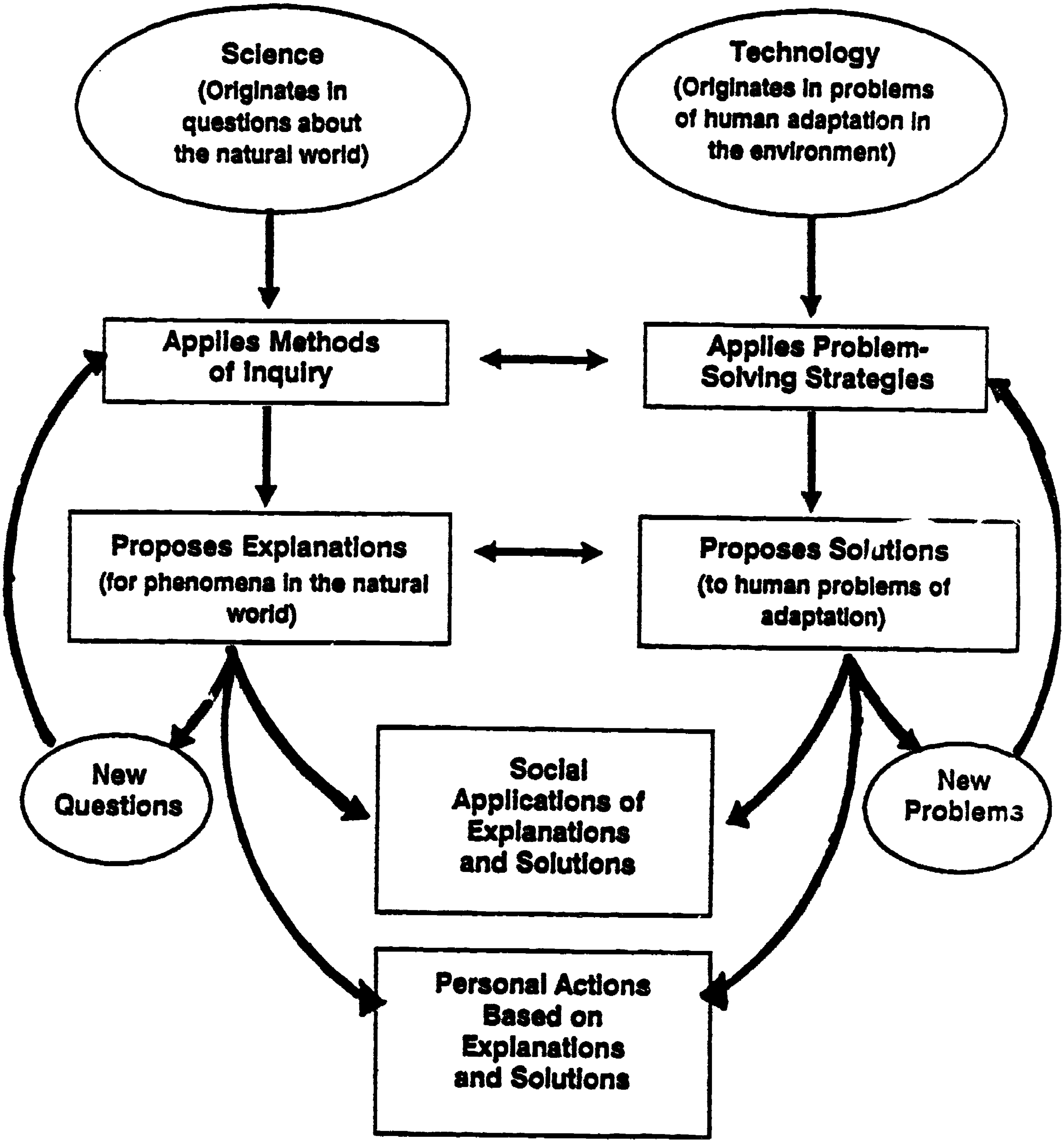

Figure 3. The relationships between science and technology and their connection to educational goals.

Source: Bybee et al., 1989, p. 12.

> analysis. Scientific methods of inquiry, on the other hand, focus on explanatory power and like criteria (Bybee et al., 1989; p. 14).

The National Center proposes that science and technology cannot be easily separated; each contributes to the other. Therefore, it is reasonable to view the contributions of science to technology and technology to science as varying along a continuum.

Drawing from such a view, the Center proposed five principles that elementary children should understand concerning the relationships between scientific and technological thinking:

> 1. Science is an attempt to construct rational explanations of the materials world.
> 2. Scientific explanations about the natural world are always tentative; they continue to evolve.
> 3. Technologies exist within the context of nature, that is, no technology can contravene biological or physical principles.
> 4. All technologies have side effects. Furthermore, just as explanations about the world are imperfect and incomplete, technological solutions to problems are incomplete and imperfect.
> 5. Because technologies are incomplete and imperfect, all technologies carry some risk; correspondingly, the degree to which any society depends on technology is also the degree to which the society must bear the burden of risk. (p. 15-16)

To help students develop this kind of thinking, the Center proposes that elementary school science programs should teach both scientific methods of inquiry and technologic strategies for problem solving. Programs should also introduce students to the relationships between answering questions and solving problems and the interactions between proposed explanations and proposed solutions. Finally, school science curricula should emphasize the personal and social utility, limits, and consequences of proposed explanations and solutions.

Assessment of STS teaching and learning. Because the STS perspective has not been implemented extensively in classrooms, there is almost no research looking at teachers' efforts to address these goals or at student learning when such a curricular focus is used. The Biological Sciences Curriculum Study group is currently piloting and revising a K-6 science-technology-health curriculum (Bybee, 1988). Analyses of their curriculum materials and the impact of instruction from these materials on student understanding of science and technologic thinking will be useful in assessments of the power of an STS framework for elementary science. Assessments in the pilot stage of this project are focused primarily on teachers' use of the materials. In the future these classrooms will provide an excellent context for in-depth studies of the impact of STS goals on student learning and understanding.

The Conceptual Change Perspective: An Emphasis on Conceptual Understanding

Desired outcomes and purposes. From the conceptual change perspective, the primary goal of science education is to help students develop meaningful, conceptual understanding of science and its ways of describing, explaining, predicting, and controlling natural phenomena (Anderson and Roth, in press; Driver, 1987; Hewson & Hewson, 1984; Nussbaum & Novick, 1982; West & Pines, 1985). 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 among concepts and facts, and is organized around key ideas in ways that make the knowledge accessible and able to provide broad explanatory power (Prawat, 1988; Roth, in press-a). This stands in contrast with knowledge that exists as isolated fragments (facts, definitions, terms, concepts) which students can parrot back for recall-focused tests but that students cannot apply and use 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 a growth view of knowledge).

This web of knowledge, or the individual's conceptual ecology (Posner, Strike, Hewson, & Gertzog, 1982), includes a tightly integrated and interdependent set of scientific concepts and processes, which only become useful and meaningful to students when they are also integrated with the learners' own personal knowledge and experiences with natural phenomena. Thus, a central goal of science teaching is to help students change their intuitive, everyday ways of explaining the world around them in ways that (a) incorporate scientific conceptual frameworks and ways of thinking into their naive frameworks, (b) empower students with increasingly satisfying and useful ways of explaining their own experiences with natural phenomena, and (c) contribute to students' valuing of science and scientific knowledge and to students' disposition to strive for increasingly powerful ways of making sense of the world around them.

The conceptual change perspective has grown out of a research tradition that has provided important insights into the difficulties students face in constructing the integrated and useful understandings of science described above and that has contributed new understandings about instructional strategies that best foster such conceptual change. The findings from conceptual change research have raised important, broad curricular issues for elementary science, but researchers in this tradition have not yet developed positions (either research-based or advocacy) about the specific content and organization that should comprise the elementary science curriculum. The challenges students face in developing meaningful understandings of science concepts suggest one important curricular issue, however: The science curriculum should focus on developing deep understandings of a few concepts rather than superficial coverage of many concepts (Anderson & Roth, in press; Bybee et al., 1989; Driver, 1983; Glaser, 1984; Linn, 1987; Resnick, 1987). To help students truly make sense of key concepts takes time. Conceptual learning is a much more difficult, complex process than has previously been assumed. Thus, important curricular decisions need to be made about what concepts to include and which to eliminate.

A curriculum that fosters the development of meaningful, connected understandings also needs to be conceptually integrated, coherent, and linked both within and across grade levels. Again, this general dictum raises questions about the elementary science curriculum rather than providing guidelines about the specific content goals of the elementary curriculum: Should the content be organized around key ideas/concepts from the traditional science disciplines (such as matter and energy, interactions in ecosystems, etc.)? Or should it be organized around science, technology, and society issues? Or should it be organized around concepts that are particularly powerful in helping students understand science in a conceptual change way? Should the elementary curriculum emulate the secondary curriculum, with yearlong sequences in the life, physical, and earth sciences? What alternatives to the typical topical approach to science teaching (plants one month, the solar system the next) does the conceptual change perspective suggest? These are questions that have not yet been systematically addressed by conceptual change researchers. Instead, their emphasis has been on the very complex and difficult tasks of studying students' learning and identifying ways to help students construct meaningful understandings. A position on <u>which</u> concepts students should understand has not yet been articulated.

Advocates of the conceptual change perspective view the development of flexible and usable scientific knowledge as being a critical goal for <u>all</u>

students, not just those students bound for science careers (Linn, 1987). Like the STS advocates they argue that a goal of science education is to develop a scientifically literate society; however, the two perspectives see different means to that end. The conceptual change perspective focuses on the conceptual nature and explanatory power of students' developing understandings of science, arguing that the way to develop scientifically literate citizens is to help learners develop rich and meaningful understandings of whatever science they study. This will enable students to understand and value science as a sense-making endeavor. Millar and Driver (1987), for example, describe the ways in which a pedagogy that promotes meaningful conceptual understandings can empower students not only to act in the here and now (the goal of developing useful knowledge) but also in the future as citizens in a democratic society:

> These are some of the characteristics of a new pedagogy which enables pupils to develop useful conceptual tools; it is a pedagogy designed to empower people to act more effectively in their daily lives, in their involvement with natural events and with technological artifacts. In addition to developing useful personal knowledge, such a pedagogy also adopts a perspective on science as public knowledge, giving pupils some understanding of the epistemological basis on which such knowledge rests. This may involve empirical work in laboratories but it also encompasses broader considerations such as the history of scientific ideas, cultural pluralism and science, the social mechanisms whereby knowledge becomes validated by communities of scientists and the interaction of science and societal concerns.
>
> Arguably the development of the sciences is one of the greatest achievements of human societies and some appreciation of it as a human endeavor should feature in our schools alongside studies of other important cultural achievements such as the arts and humanities. But it is not only on aesthetic grounds that a case is made for giving pupils an understanding of the nature of the scientific enterprise. Just as personal knowledge of science empowers pupils to act in their everyday lives, so a critical appreciation of the way scientists work empowers them, as future citizens in a participatory democracy, to query, question and seek alternative views on scientific and technological decisions which affect their lives. (pp 57-58)

The STS perspective, in contrast, has approached 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. Proponents argue that a disciplinary-focused curriculum meets the needs of only a few students. To capture the interest of all students, the content of the science curriculum needs to shift. These arguments are not based on how students learn and make meaning but rather are based on current science and society issues that today's citizens should understand and grapple with. Thus, if the goal of science education is to create citizens who can make informed decisions about science and society problems, then the school curriculum should treat students as little science citizens (much as the inquiry perspective treats learners as little laboratory scientists) who are involved in "doing" problem solving about current science and society issues. There is an apparent assumption that practice in working through current problems will have two benefits: It will be interesting and motivating to students, and it will help students develop the decision-making and problem-solving skills they will need in the future to deal with new issues and problems that will arise. STS advocates do not see knowledge of the traditionally taught, disciplinary-bound ideas of science as particularly powerful or useful in preparing students to become effective science citizens.

Although conceptual change (CC) advocates are not committed to maintaining the disciplinary focus of the science curriculum, it is easy to imagine the kinds of arguments they might make before abandoning this disciplinary knowledge as an important part of the science curriculum:

> CC spokesperson: How can you talk about changing the content of the science curriculum just as we are beginning to get a better handle on how to help kids develop meaningful understandings of the content that we've been teaching? What makes you think kids are going to understand science better just because you are giving them new content? Aren't you just giving them new content to not understand?

> <u>STS spokesperson</u>: Most kids, especially young kids, will never make sense of big concepts in science-such as matter and energy--because it's just too abstract for them, too remote from their experience. Why not give them some content that is relevant to their lives?
>
> <u>CC</u>: I agree that it is critical that links be made to students' personal experiences, but "matter" and "energy" can be linked to their experiences in meaningful ways. And don't they need some basic understandings of these concepts before they can do meaningful problem solving and decision making about energy resources, about recycling, etc.?
>
> <u>STS</u>: But the big concepts in science are just not inherently interesting to most students. Like photosynthesis--what kid really cares about how plants make food as long as they know how to take care of the plants in their gardens? Wouldn't science come much more alive for students if you talked about the dilemmas we face in deciding whether or not to use fertilizers and pesticides in agriculture? Kids could get really involved in their learning by arguing the pros and cons of issues like that.
>
> <u>CC</u>: It sounds like you want students to solve problems and make decisions without a sound conceptual framework in place to use in such decision making. Yes, I think the farmer's plight with fertilizers would be an excellent way to deepen students' understanding and appreciation of concepts like photosynthesis or ecosystems. It would show the usefulness of knowledge about photosynthesis in explaining and controlling the "real" world. But without that conceptual tool--the knowledge about photosynthesis and the difference between food that plants make and fertilizers they take in from the soil--isn't the decision-making process trivialized? Do we want citizens who make decisions without a solid knowledge base?
>
> <u>Inquiry spokesperson</u> (interrupting): But both of you make it all sound too neat, too orderly. These are elementary kids we're talking about! The best way to get <u>all</u> students interested and involved in science is to let them mess about with nature and with science and not worry too much about how deeply they understand particular concepts. They're not ready yet to understand in a meaningful way either the big ideas of science or the big issues society faces. Just let them get a feel for the kinds of questions and issues science explores and help them develop the process skills that they'll need later on to develop more sophisticated understandings.

Thus, the advocates for the three perspectives agree that all students should experience and learn about science. But they disagree about the kind of science that all students can and should understand, about the ways students learn and are motivated to learn science, and about the kinds of curriculum and instruction that will enable science to reach all students.

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Historical and theoretical background. Of the three perspectives discussed in this paper, the conceptual change perspective is the only one that did not originate initially in response to social/political conditions. In contrast, it is a research-based perspective that has grown out of cognitive science studies of learning and knowing in complex knowledge domains (DiSessa & Ploger, 1987; Resnick, 1983; Tweney & Walker, in press). This line of research, including a rapidly growing body of research looking particularly at science learning, has attempted to articulate the nature of both expert and novice knowledge and to describe how that knowledge grows and changes (Chi, Glaser, & Rees, 1982; Larkin, McDermott, Simon, & Simon, 1980a, 1980b). Important contributions from this knowledge-based study of learning include (a) a richer and less linear view of the nature of science and expert knowledge in science and (b) a new understanding of why it is so difficult for students to develop useful, conceptual understandings of many of the subjects they are taught in school. The conceptual change perspective is built on constructivist views of knowledge growth both in science and in individual learners (Champagne & Klopfer, 1984; Driver & Oldham, 1986; Erickson, 1984; Shuell, 1986).

a. *Nature of science and expert knowledge in science.* Studies of expert learning and problem solving and recent philosophy of science both highlight the importance of conceptual frameworks in learning, reasoning, and problem solving. In summarizing findings from studies of expert and novice cognitions, Glaser (1984) emphasized the central role of domain-specific knowledge in enabling and shaping higher level thinking and problem solving. Experts in various domains hold well-structured conceptual frameworks or schemas that include knowledge about the usefulness of that knowledge in a variety of specific situations. These experts are not expert because they have highly developed, abstract reasoning skills; rather, the findings suggest that experts are able to reason in expert ways because of the well-structured and functional knowledge of specific content and concepts in a particular domain.

Glaser cites several studies that show how children's or novices' abilities to reason at abstract levels are improved as a result of new conceptual knowledge structures. With Driver (1983) and others (Carey, 1986; Kuhn, 1986; Resnick, 1987; Rumelhart & Norman, 1981), he concludes that conceptual understanding is at the heart of what is traditionally called higher level thinking, self-regulated learning, and problem solving:

> Thinking is greatly influenced by experience with new information. Change occurs when theories are confronted by specific challenges and contradictions to an individual's knowledge. (Glaser, 1984, p. 98)

Thus, studies of experts' knowledge have begun to unravel and examine the nature and role of conceptual understanding and its relationship to reasoning and higher level thinking. The idea that an individual's knowledge structure drives the kinds of reasoning that he or she is capable of doing is paralleled in recent views of the nature of knowledge growth in science itself.

An inductivist or empiricist view of the nature of science assumes that knowledge grows out of observation. Scientific concepts, laws, principles are discovered by rational induction based on observable facts. Scientific knowledge gradually grows as more and more facts are uncovered by increasingly sophisticated methods of observation. This is a view of science that is represented in many school curricula as "the" scientific method and is certainly evident in many of the process-focused school curricula. "Doing" science in this view means making observations and deriving important ideas from those observations through a logical, step-wise thought process.

An alternative constructivist view of science points to limitations in the inductivist view and emphasizes the ways in which scientists' knowledge and theories <u>interact with</u> their experiences and observations of the real world.

This paints a much richer and messier view of knowledge growth in science. Scientists' current knowledge has a critical influence on the ways in which they observe and perceive the natural world; thus, scientific theories do not grow directly from observation but are constructed by humans who are constantly testing and evaluating their conceptual frameworks against actual data from the real world.

Thus, scientists' conceptual frameworks are at the heart of the scientific endeavor and are not viewed simply as the outgrowth of specific scientific processes (the scientific method): The conceptual frameworks shared by scientists also drive what scientists observe and pay attention to, what questions they ask, the kinds of experiments they design, and so on. Conceptual frameworks shared by the scientific community may remain unchanged for long periods of time not because these frameworks are immutable truths but because the kinds of questions and observations scientists make are influenced by the accepted conceptual framework. The longer a view is accepted and supported by observation, the harder it is for scientists to recognize data that challenge the view.

b. *A constructivist, conceptual change view of learning.* The bulk of the research that has helped shape the conceptual change perspective has involved detailed analyses of learners' ways of understanding particular science concepts. Extending the work of Piaget, this research has analyzed not only the reasoning processes that learners use but also the role that the learner's conceptual knowledge plays in the learning/reasoning process. Insights about the critical role that students' existing knowledge structures play in the learning process have led to a view of the learner not as an empty bucket that passively receives any new knowledge that is poured in but as an active constructor of new knowledge whose prior knowledge shapes the way new knowledge is perceived and how it is integrated into the learner's schema or way of making sense. In this constructivist view of learning, what the learner already knows drives what he/she pays attention to and how new knowledge is understood (Anderson, 1987; Carey, 1986; Champagne & Hornig, 1987; Champagne, Klopfer, & Gunstone, 1982; Driver, 1986; Linn, 1987, in press;, Resnick, 1983; Osborn & Wittrock, 1983; Tobin, 1988). This makes learning new concepts a much more complex, challenging, and messier task than previously assumed.

In a tabula rasa view of science learning, students' difficulties with science can be explained by the newness and abstractness of scientific terms and concepts and by the students' lack of prior knowledge about these terms and concepts. Learning about photosynthesis, for example, is difficult because the learner has never heard of that word before, has no understandings of chemical reactions, molecules, cells, or chlorophyll--there is a lot of new information to learn before photosynthesis will be meaningful. However, the conceptual change research points to a more powerful explanation for students' learning difficulties than their lack of prior knowledge. A bigger problem is that students often have very rich prior knowledge about many of the phenomena they study in science class, but that knowledge is in conflict with scientific explanations presented in science class. Students may not know the word "photosynthesis," for example, but have a lot of everyday knowledge related to this concept. They "know" for example, that plants need food and that plants get their food like people do--by eating. The roots are like mouths that take in food from the soil. This explanation conflicts in critical ways with scientists' understanding about plants' unique and critical ability to use light energy to make their own energy-containing food internally out of nonenergy-containing materials (water, carbon dioxide) taken in from the environment.

But the students' explanations have been constructed based on their own experiences with real plants, and these explanations make personal sense.

Numerous studies have demonstrated how difficult it is for students to give up or change these personal theories (Champagne et al., 1980; Clement, 1982; Gilbert & Watts, 1983; Roth, Smith, & Anderson, 1983; Trowbridge & McDermott, 1980). The personal theories shape the way students perceive and interpret both explanations provided to them by teachers and textbooks and observations of natural phenomena. Thus, meaningful learning in science requires students to go through a very difficult process of conceptual change in which their own way of thinking and viewing the world must be reconciled and linked with new conceptual scientific frameworks.

In this conceptual change view of science and science learning the traditional distinctions between science content and science processes as well as the distinction between conceptual understanding and higher level thinking are problematic. Conceptual understanding is not seen as distinct from either the thinking processes of science or from higher level thinking. Ways in which these traditional distinctions may misrepresent the nature of science and scientific thinking and be translated into pedagogies that fail to promote meaningful conceptual change learning are discussed in the next two sections.

Relationships among science content, process, and attitudes. The philosophical and psychological basis of the conceptual change perspective described above points to the centrality of conceptual knowledge and conceptual frameworks as tools in science and science learning. However, this is not to say that conceptual change advocates view science as primarily a body of knowledge to be learned through a traditional, didactic approach. Rather, this perspective argues that scientific thinking is conceptually driven and that the so-called scientific processes are intimately linked to scientific conceptualizations. Therefore, the conceptual change perspective calls for the integration of science processes and conceptual knowledge, in ways that better reflect both the richness and complexity of science itself and in ways that more effectively map onto students' ways of learning science (Johansson, Marton, & Svensson, 1985; Marton & Ramsden, 1988; Millar & Driver, 1987; Ramsden, 1988).

An examination of how scientists use conceptual knowledge and the science reasoning processes suggests the importance of integration of conceptual knowledge and science processes. Expert scientists do not hypothesize, observe, 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 <u>drive</u> 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, the arts, or any other domain, 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. A good scientific observation, in contrast, focuses on key features in ways that will contribute new knowledge, increase the explanatory power of a particular conceptual framework, generate new understandings of relationships among concepts, or raise significant questions about accepted conceptual frameworks. The scientist who makes such critical observations does not just happen to see what others have not seen because of expert "observation skills." To set up the conditions in which important observations are made, the scientist draws from existing conceptual knowledge, asks questions about important pieces of the framework, develops hypotheses, and designs experiments that will permit the critical and relevant observations to be made.

The importance of the observation is not how accurately the scientist can detail and describe all facets of the observed phenomenon but how the scientist focuses the observation and uses the observed phenomenon to develop more powerful and complete explanations--in how useful the observation and the scientist's interpretation of the observation is in refining, changing, and challenging conceptual frameworks shared by the scientific community. Thus, skillful expert observation is intimately linked with both conceptual knowledge and with all of the other "processes" of science. As Millar and Driver (1987) argue, each of the so-called scientific "processes" can be submitted to a similar critique. These processes are not meaningful in isolation, and they and are not science in the absence of a scientific conceptual framework.

Millar and Driver (1987), in their critique of this view of science in which science processes are isolated from science concepts, describe how such a separation has been translated into school curricula in ways that have not been responsive to the research on how students learn in science. Their argument supports findings in my own research in which inquiry- or process-focused teaching left students like Rachel [see p. 44] (Roth, Smith, & Anderson, 1983) with a misleading picture of science as "doing" for doing's sake and with personal theories unchallenged and unchanged as a result of weeks of process-focused instruction. Students did not view the process of science as helping them better understand their world. In many of the inquiry curriculum materials, for example, students are engaged in practicing the various scientific processes, with "content" and particular concepts eliminated as much as possible from instruction. Such curricula rest on the assumption that students learn to do science by practicing these process skills:

> By basing the syllabuses firmly on the idea of discovery methods, the pupil is required to react continuously in a thinking situation; he learns by hypothesizing and discussion, by experimenting, by

> measuring, and by reassessing his hypothesis in the light of experimental results. (Scottish Education Department, cited in Millar & Driver, 1987, p 34)

But the conceptual change research reveals that students, even very young students, "practice" the processes of science all the time as they strive to make meaning of their personal world (Carey, 1986; Easley, in press). They make observations, raise hypotheses, and test them out in constructing their personal theories of natural phenomena. Students who believe plants take in food from the soil, for example, have used their own observations of both plants and people to construct this explanation of how plants get their food. Of course, their observations are limited in important ways--they cannot see into plants and watch photosynthesis occurring in leaf cells. But will content-free exercises designed to improve observation skill help students change their personal theories of how plants get their food? Will such exercises make students aware of what they need to pay attention to in their observation of plants in order to develop a more satisfying explanation of how plants get their food?

Students have the capacity to observe, to classify, and to make inferences. Providing opportunities for them to practice these processes in isolation does not help them understand how these processes are useful in understanding the world. What <u>will</u> help students understand the richness and power of scientific endeavors is learning how these processes can be helpful in developing increasingly meaningful explanations of the world. Instruction that involves students in using these scientific processes to change their own theories in ways that provide them with explanations that are both more personally meaningful and also more consistent with scientific explanations provides a powerful alternative to process-focused instruction.

In order to make such changes in their conceptions, students need to do very difficult cognitive and metacognitive work. Much of this cognitive work could be described as engaging in science processes (predicting, hypothesizing, observing inferring, etc.), but students do not practice these processes in isolation and the goal of their work is not simply to become better observers or predictors. This cognitive work also requires metacognitive thinking processes. Students need to be able to identify when they are confused and to develop plans for resolving conceptual conflicts and monitoring progress. But students do not undergo change in <u>conceptions</u> by learning and practicing these metacognitive strategies in content-free contexts. Instead, these science and metacognitive processes are used in the service of developing better explanations of natural phenomena. Such an integrated approach to science learning provides students with richer understandings of both the content and the processes of science.

Marton and Ramsden (1988) make a similar critique of the relationships between content and process in a conceptual change view of learning. They criticize both educational research and classroom teaching that promote learning of broadly generalizable thinking skills in isolation of particular content. They use the example of attempts to teach students metacognitive skills independent of content and context. If the kind of learning we want students to develop is genuine understanding ("a qualitative change in a persons' way of seeing, experiencing, understanding, conceptualizing something in the real world") as opposed to simple recall, it is logically impossible for learning to be defined as content and context-free:

> Learning techniques and instructional strategies are inextricably linked to subject matter and the students' perceptions (of the subject matter). . . . In our understanding, while one can separate process and content analytically, the two aspects simply cannot exist without one another. There is obviously no learning without a

> content--you have to learn something. And there cannot be any learning without an act of learning--something has to be learned in a certain way. (pp. 7-10)

Where do scientific attitudes fit into this? In the conceptual change view, students' attitudes toward science and science learning are tightly linked to this integrated view of science processes and content. As students are helped to develop more powerful and personally meaningful explanations of particular phenomena and concepts, they will gradually come to value science and scientific investigation. As they are helped to change their personal theories and integrate them with alternative explanations posed by scientists and with their own personal observations, they will gradually develop dispositions to raise questions about their own and others' theories, to struggle with alternative viewpoints, and to have conceptual change sense-making as a goal for their science learning. Thus, positive attitudes and desirable dispositions toward science and science learning do not grow out of the nature of classroom activities--that it's fun to do experiments. Nor do they grow out of the nature of the content--that science is good if it's not about difficult stuff like molecules and energy and matter but rather is about current issues like pollution, acid rain, toxic wastes, and nuclear power. Rather, positive attitudes and dispositions to puzzle about the natural world and to be skeptical grow out of students' experiences in constructing meaningful understandings. As students experience the satisfactions and rewards of conceptual change sense making, their attitudes toward science as a sense making endeavor develops and their disposition to take a questioning, critical stance grows.

<u>Conceptual understanding and higher level thinking</u>. Cognitive psychologists' analyses of expert/novice thinking and learning in science and philosophical analyses of knowledge growth in science have led to insights about the nature of scientific thinking and about the relationships between conceptual

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knowledge/understanding and higher level thinking. From a conceptual change perspective, two insights that have important curricular and instructional implications grow out of these studies of scientific thinking in both experts and in children.

First, the traditional representation of conceptual knowledge and science processes as separate kinds of scientific thinking does not accurately reflect what we have learned about the nature of science or about the nature of science learning. Conceptual knowledge and the so-called scientific processes or thinking skills are intimately interwoven (as described in the previous section). Conceptual knowledge both influences and is influenced by scientific thinking processes and experimentation.

This dichotomous view of scientific thinking has led to curricular changes and instructional practices that have not improved students' understandings of science. Such a view is reflected in assumptions that there are basically two ways one can organize the science curriculum and teach children about science. One can emphasize science processes and thinking skills and engage students in hands-on activities to accomplish this goal. Alternatively, one can organize the curriculum around science concepts and content and teach students in a didactic, textbook-focused way. The conceptual change research has shown that neither of these approaches has helped the majority of students develop either meaningful, conceptual understandings or higher level thinking skills, much less an integrated understanding of them. Although there is rhetoric in the schools and in existing science curriculum materials that both science concepts and science processes should be taught and emphasized equally, the tendency to think about scientific thinking as <u>either</u> conceptually focused or process-oriented prevails. The resulting "integration" of concepts and processes in school curricula and in school classrooms ends up not to be an integration at all but more like a balancing of competing goals. After three days of content-focused teaching, for example, it's time for some activities and process-focused teaching. The activity selected to teach such process thinking may or may not be closely linked to the concepts being read about in the textbook.

For example, in a fifth-grade unit in the most popular science textbook series in the United States, (Silver Burdett & Ginn Science, Mallinson, Mallinson, Valentino, & Smallwood, 1989) the textbook chapter presented a number of concepts and facts about activities of green plants (photosynthesis, respiration, transport of materials, reproduction). Provided along with this content coverage were supplementary worksheets designed to develop students' process skills. The worksheets for this particular chapter were titled "Critical thinking," "Sequencing," and "Observing and Inferring." Notice the lack of reference to any concept or content knowledge in the focus of these worksheets. And although all of the worksheet exercises related to plants, they did not link closely to the particular concepts about plants that were developed in the text coverage.

For example, the critical thinking worksheet included a short text passage about insect-eating plants followed by a series of critical thinking questions. Students were asked to identify the mechanical, electrical, and chemical processes involved in the closing of the Venus flytrap's leaves. The text chapter never talked about the differences between mechanical, electrical, and chemical processes, and students were expected to complete the critical thinking exercise without any explanation or development of the meaning of these concepts. Thus, the worksheet introduced new concepts for students to use as they "practiced" critical thinking. And none of the critical thinking questions engaged students in linking their study of concepts covered in the text, such as photosynthesis, to this new information about plants that "eat" insects. Thus the critical thinking exercise was not designed to help students develop deeper understandings of concepts that were presented in the text. Students could do the critical thinking activity without reading or studying the concepts developed in the student text. The curriculum developers assumed that teachers would elect to use at least some of the process worksheets in order to <u>balance</u> the content focus of the text itself. Thus, the curriculum developers reflected this dichotomous view of scientific thinking by suggesting that content teaching and process teaching could be taught independently of each other.

In contrast, the conceptual change research on students' learning emphasizes the importance of taking students' personal conceptual frameworks seriously in helping students understand the nature of science and scientific thinking. The kinds of thinking that scientists do become understood and valued by students when these thinking processes help them change their own explanations of phenomena in ways that provide more powerful and personally meaningful understandings of the natural world. This suggests a view of instruction in which conceptual understanding is the goal, and the development of such understanding is seen as requiring the use of a variety of what are typically called higher level or process thinking skills.

Second, hierarchical views of scientific thinking are problematic because they imply that conceptual understanding is a relatively straightforward, lower level process that students need as a basis for doing higher level thinking. This view does not capture the ways in which thinking processes typically labelled as "higher level" are an integral part of the development of meaningful, conceptual understandings. In my own studies of individual learners who successfully integrated ideas about photosynthesis into their personal conceptions about how plants get their food, I found these students using a variety of higher level thinking skills in the process of developing conceptual understandings. These students did not treat new knowledge as facts to be memorized but instead continually tried (with the support of their texts and teachers) to use new information to explain and make predictions about the world. Often this was a difficult and confusing process, as students encountered areas where their knowledge was incomplete or in conflict with scientific ideas being presented. Such conflicts led to analyses of the differences between them and to restructuring of students' personal conceptual frameworks. Students used experimental observations as well as teacher explanations as sources of information to help them rethink their ideas.

These students were metacognitively active, monitoring their developing understandings, recognizing areas of confusion, and seeking to resolve them. In the end, they developed conceptual understandings that they could use to explain a variety of everyday phenomena. Their ability to use the concepts in these application situations was a *reflection* of their conceptual understanding rather than a higher level thinking skill that was developed after their conceptual understanding was in place (as suggested by taxonomies like Bloom's that place "application" as higher level than "knowledge."). Thus, these students' conceptual learning was not straightforward, bounded, lower level thinking. Rather, their learning was a complex, intellectually active process of conceptual change, in which their entering understandings of how plants get their food were substantially restructured and integrated with their personal theories.

This process of conceptual learning required the integration of a variety of sophisticated, higher level cognitive and metacognitive thinking skills. Therefore, conceptual understanding *is* a higher level process that involves a variety of kinds of higher level thinking skills. Ramsden (1988) concurs with this view, describing the changing of conceptions as the most fundamental aspect of learning and as a thinking process itself. The important point is that a view of conceptual knowledge as less complicated thinking than application, explanation, synthesis, and so forth, is misleading. Development of meaningful conceptual knowledge is a complex process, involving many kinds of what is generally referred to as higher order thinking.

A hierarchical view of scientific thinking and learning becomes even more problematic when we consider the hierarchical view of science "process" skills (with observing and classifying categorized as simple process skills and processes such as inferring and controlling variables as higher level skills). This view of scientific processes misrepresents the nature of scientific thinking by suggesting that some processes are easier to understand and use than others and that these processes can be identified and used in isolation from each other and from conceptual knowledge. This has been translated into curriculum materials and science methods texts that advocate the teaching of process skills in isolation, with the easier processes (observing, classifying) being appropriate for lower elementary children, and higher order processes (like inferring) being appropriate only for older students. Both Norris (1985) and Millar and Driver (1987) argue articulately about the complexities of even the "simplest" science process goal. As discussed in the last section, for example, observing scientifically is a complex process that is closely tied to a person's conceptual framework and that requires a variety of kinds of higher level thinking.

Summary. Figure 4 summarizes the conceptual change perspective. It illustrates that conceptual understanding results only when learners can use scientific processes to reorganize and integrate their own everyday knowledge with scientific conceptualizations. Development of such useful conceptual

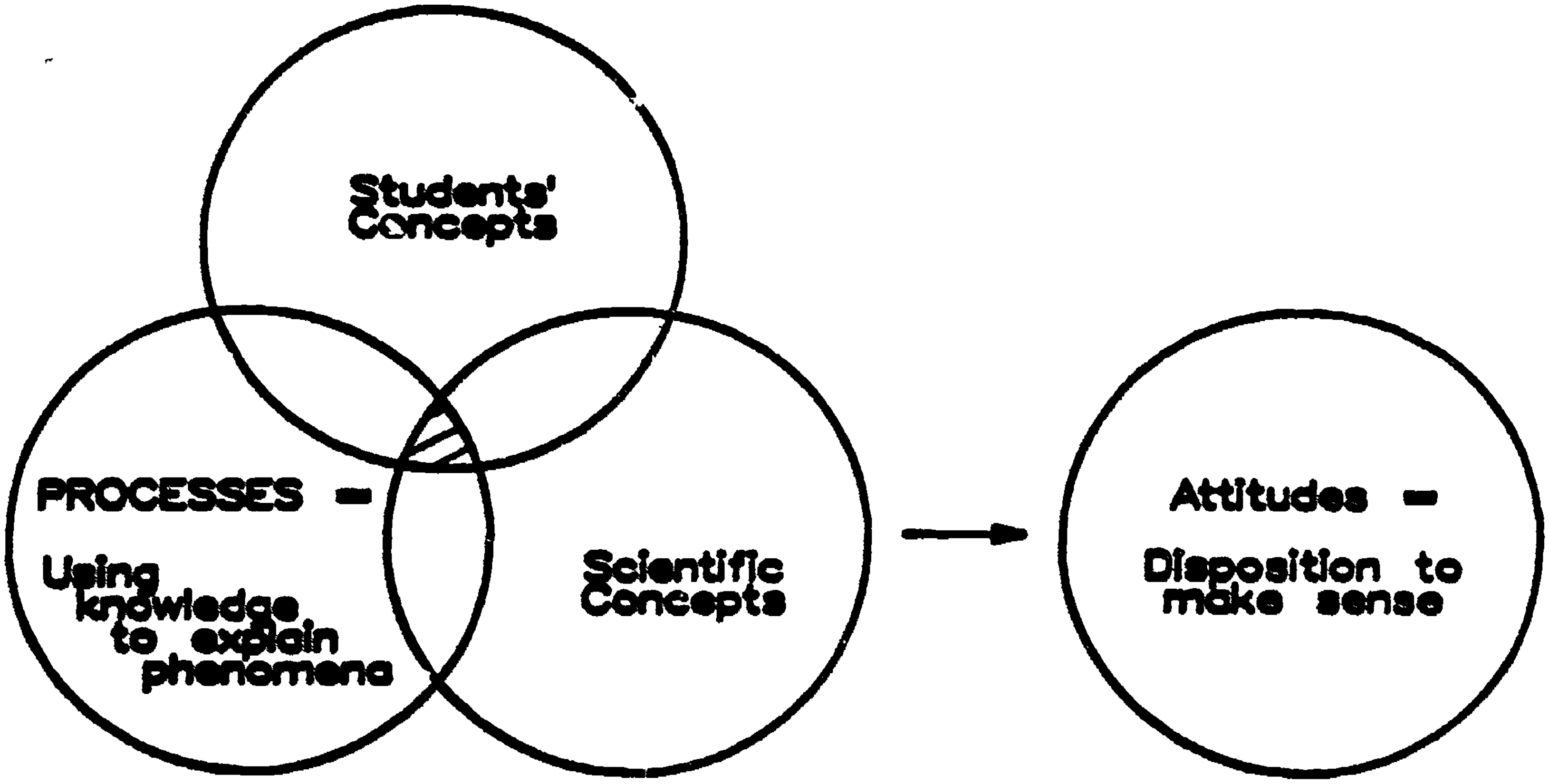

Figure 4. Relationships among science concepts, processes, and attitudes in a conceptual change perspective. (Shaded area indicates conceptual understanding and higher level thinking.)

understanding is the heart of higher level thinking in science. As learners experience the rewards of understanding phenomena and concepts in meaningful, useful ways, they will be encouraged to pursue their learning of science as a sense-making, problem-solving endeavor. Thus, they will develop the disposition to be genuine inquirers who believe that they can develop increasingly complex and satisfying explanations of the natural world.

Assessments of conceptual change learning. Most of the work on assessment in the conceptual change tradition has focused on detailed analyses of students' conceptions of a wide variety of topics (Anderson & Smith, 1983; Bell, 1981; Champagne et al., 1980; Clement, 1982; Driver, Guesne & Tiberghien, 1985; Erickson, 1979; Helm & Novak, 1983; Johnson, Wellman, 1982; McCloskey, 1983; Novick & Nussbaum, 1981; Nussbaum, 1979; Nussbaum & Novak, 1976; Osborne & Freyberg, 1985; Roth, Smith & Anderson, 1983; Stead & Osborne, 1980). These analyses have provided critical insights about the role of prior knowledge in the learning process, about students' strategies for learning science, and about new methodologies for assessing conceptual understanding.

One methodology that has been used extensively in this research tradition is the detailed, clinical interview. Clinical interviews probe the learners' knowledge and thinking through a series of tasks that engage students in explaining scientific phenomena and concepts in the context of everyday experiences and/or specific problem-solving activities. Such detailed interviews can be used to construct maps of the cognitive structure of students' conceptual and procedural knowledge. Such interviews have been used in combination with classroom observations to detail the process of conceptual change and the role of instruction in promoting or constraining that change (Nussbaum & Novick, 1982b, Roth, 1984; Roth, Anderson, & Smith, 1987).

Paper and pencil tests have also been designed to elicit students' conceptual schemes in ways similar to the clinical interview approach. Such tests emphasize students' explanations of phenomena. Instead of asking questions that elicit students' recall of science facts, questions are designed to elicit students' real world understandings of phenomena. Instead of asking, "What is photosynthesis?" for example, we have asked students

> Do green plants need food? (Roth, 1985a, p.370)
>
> Write down _your_ ideas about how plants get their food. (Roth, 1985a, p. 370)
>
> Describe what food is for plants. (Roth, 1985a, p. 370)
>
> Do green plants need light? Why? (Roth, 1985a, p. 370)
>
> A box was placed over the top of a plant so that the plant was covered except for one leaf. The plant was watered and had plenty of air but only that one leaf could get any sunlight. What do you predict will happen to the plant? Why? (Roth & Anderson, 1987, p. 28)

By asking a series of such questions and aggregating evidence from students' responses to several different questions, we can describe the strength of a student's commitment to a particular scientific conception or to or an alternative, personal conception. Because these tests rely heavily on students' written explanations, coding schemes to score the features of students' responses are much more complex than scoring multiple choice format tests; however, reliable coding can be achieved. We have also experimented with multiple choice format questions in which foils are designed to capture particular kinds of common student misconceptions:

Most plants get food (you may circle more than one if needed)
- a. from soil
- b. from air
- c. from water
- d. by making it themselves
- e. I don't know

For plants food means
  a. water
  b. water, soil, air, & light
  c. water, air, & light
  d. fertilizers & minerals in the soil
  e. something plants make
  f. I don't know. (Roth, 1985a, p. 373)

These kinds of assessments of student learning stand in contrast with both the typical assessment practices of classroom teachers and the kinds of state and national assessments of science learning currently being used. Existing tests (especially those provided with science textbook series) tend to ask many content-focused questions that are at the rote or recall level and that emphasize scientific terminology. "Higher level" questions are largely limited to process-focused tasks that are designed to be answered independent of particular content knowledge (interpreting a graph, predicting an outcome, identifying whether or not an experiment has a control). The conceptual change assessments, in contrast, focus primarily on assessing students' abilities to use particular concepts to explain everyday phenomena or experiences. Thus, the tests assess meaningful, integrated conceptual understanding.

Conceptual change advocates assert that inquiry or process-focused assessments that are isolated from conceptual assessments do not add critical information to our knowledge of student learning in science. Because these tests are designed to be "content-free," they tell us no more about the state of student learning and knowledge than recall-focused content tests. Millar and Driver (1987) point out that although the inquiry-oriented tests are designed to be content-free, they cannot in fact be free of content. Students who are asked to observe pictures of trees and to notice the differences among them or to make hypotheses about them may score differently on their "observing skills" or "hypothesizing skills" because of differences in experience with and interest in trees, not necessarily differences in observing or hypothesizing ability. Millar and Driver identify another problem with such process assessments: They assume that because the students can identify differences among trees, for example, that they have displayed the ability to observe. There is little attempt to distinguish levels of observation skill or to assess students' observation skill as embedded in complex, conceptual domains. Process assessment remains isolated from content assessment.

Would it be possible to develop state or national assessments that assess meaningful, integrated conceptual understanding? The assessments used in conceptual change research have provided a much richer picture of the nature of student learning and understanding than existing methods of assessment. However, they are much more time-consuming to create, to administer, and to score. Another problem is that these tests are closely tied to particular conceptual knowledge. It is easy to see how textbooks could incorporate such tests into their format, because the tests come at the end of specific content-focused chapters; assessment is closely linked to instruction. But how would this work at the state and national level?

If a fifth-grade test asked students to explain a situation involving the role of light in seeing, we would hope to see differences between students who had studied about light and students who had not. Therefore, assessments would need to link closely with instruction. This implies either state or national guidelines about concepts to be covered at specific grade levels or tests that can be shaped at the local level to reflect the particular concepts taught. For example, test developers could develop large sets of explanation questions appropriate for fifth graders on a wide variety of topics. Teachers at the local level could select the four to five topics on which their students would be evaluated. Efforts pursuing testing alternatives that probe students' understanding and ways of thinking in deeper, richer ways are currently being explored (Anderson, 1988; Baron, 1988, Chittenden, 1984, 1988; Raizen et al., 1989).

Assessments of conceptual change instruction. Although there has been extensive research in the conceptual change tradition focused on assessments of students' knowledge states, there have been fewer efforts to implement and to assess the effects of conceptual change approaches to instruction. Can a conceptual change of model of instruction be incorporated into regular classroom instruction in ways that will promote the development of meaningful and useful scientific understandings? While a number of studies have explored this question at the secondary and college levels (Champagne, Gunstone, & Klopfer, 1983; Hewson, 1983; Kuhn & Aguirre, 1987; Minstrell, 1982, 1984; Nussbaum & Novick, 1982b; White, 1984), there have been only a few efforts to study elementary science instruction that has a conceptual change orientation (DiSessa, 1982; Nussbaum & Sharoni-Dagan, 1983) and these studies involved special instructional contexts (student interacts with a computer program or audio-tutorial lessons) rather than regular classroom settings. Several efforts in regular classrooms are underway, but reports of the impact of these have either focused on changes in the teachers' knowledge and behaviors rather than on student learning outcomes (Smith & Neale, 1987) or have not yet reported student learning outcomes (Brook & Driver, 1986; Driver et al., 1987).

The work that my colleagues and I have done at Michigan State University over the last seven years has involved observation and analysis of both teachers and middle grade students (grades 5-7) and the ways in which instruction supports or fails to support conceptual change learning. Our assessments of the effects of instruction typically included multiple sources of evidence: Classroom observations of instructional units, teacher interviews, student pre- and posttests, student interviews, and focused observations and analyses of target students and their work. The results of that research are reported in a series of papers. A number of those papers report case studies of individual teachers and their students (Anderson, Belt, Gamalski, & Greminger, 1987; Eaton, Anderson, & Smith, 1984a; Hollon, Anderson, & Roth, in press; Roth, 1984, 1987; Roth, Anderson, & Smith, 1987; Slinger, Anderson & Smith, 1983; Smith & Anderson, 1984; Smith & Sendelback, 1982). Other papers report quantitative frequencies of various types of teacher behavior and their relationship to student learning outcomes (Anderson & Smith, 1983b; Blakeslee & Anderson, 1987). Although a wide variety of analytical systems and categories was used in developing these reports, the research in toto warrants several generalizations about the activities of teachers and students in science classrooms.

The most important generalization is that conceptual change instruction that engages students in integrating their own conceptions with scientific explanations and that actively involves students in using scientific knowledge to describe, predict, explain and control their world can have a significant impact on student learning. Table 5 shows that teachers who used the conceptual change curriculum materials that we developed were able to help more of their students understand and use important concepts than teachers who used either didactic or discovery oriented approaches. These successes were accomplished despite the facts that these teachers had limited opportunities to study the research and philosophy behind the materials and that they were using the alternative materials for the first time. In the classrooms where we did not intervene, even the most knowledgeable and dedicated teachers were only connecting with the small percentage of students (10-20%).

Table 5

Results of Studies Comparing Student Learning in Classrooms Using Commercial vs. Conceptual Change Materials

Topic and Grade Level	Reference	Number of Classrooms per Group		Percentage[a] of Students Understanding Goal Conception	
		Expt.	Control	Commercial Materials	Experimental Materials
Light and vision (fifth grade)	Anderson & Smith, 1983b,	6	5	18	58
Photosynthesis (fifth grade)	Roth, 1984	1	1	5	57
Photosynthesis (middle school)	Smith & Anderson, 1987	8	5	28	60
Respiration (middle school)	Smith & Anderson, 1987	4	9	12	23.5

[a] Percentages are averaged across several important conceptions in each case.

Although we can summarize results in charts quantifying percentages of students holding goal conceptions at the end of a unit and frequencies of particular kinds of teaching behaviors, qualitative analyses of these various sources have provided additional insights about aspects of learning that go beyond knowledge of particular concepts. For example, such analyses have shed light on issues related to students' motivation to learn (Lee, 1989), strategies for learning science (Roth, 1986), understandings of the nature of science, and individual differences in learning science. Case studies we have developed illustrate, for example, how content-based discourse that is more focused around students' ideas and that engages students in constructing and reconstructing explanations (i.e., not just focused around memorizing the textbook) can model for students ways to structure and regulate their independent learning. It also can help them set goals of sense-making rather than mere task completion (Anderson & Roth, in press; Roth, 1986).

"Thinking scientifically" for many students in traditional science classrooms, for example, generally means getting right answers. In one of my own studies, I analyzed students' approaches to getting those right answers. Students had a variety of strategies for getting right answers that had little to do with making sense or understanding. In contrast, students who used conceptual change instructional materials that engaged them in developing and reconstructing their own explanations of scientific phenomena succeeded in making sense of important scientific concepts and talked with pride about the progress they had made in their thinking. These students had begun to understand that scientific thinking is confusing and messy at times, is shaped by interactions with others' ideas as well as by first hand observations of phenomena, and helps you get better at making sense of phenomena in your personal world. Driver and her colleagues (1987) are pursuing similar lines of inquiry, focusing on the changes in classroom discourse and in the quality and frequency of student participation over time.

More assessment of the impact of conceptual change instruction is needed. There are important questions needing further investigation: Will successes in learning in individual units have long-lasting impact? What kinds of support and teacher knowledge are needed to use conceptual change teaching strategies effectively? How can a conceptual change curriculum walk the fine line between encouraging genuine student debate and exploration of alternative viewpoints and developing student understanding of accepted scientific theories and concepts? How is the answer to that question the same or different for first graders versus fifth graders? Despite the fact that many questions remain unanswered, the success stories in the instructional studies, suggests an important power to the conceptual change models.

The Perspectives Enacted: Implications for Instruction and the Role of the Teacher

What view of instruction and the role of the teacher do each of these curricular perspectives suggest? To what extent does each perspective provide teachers with a teaching/learning framework or model that is both manageable in the classroom and supportive of meaningful student learning? To further illustrate the differences and similarities among these perspectives, I will describe how a unit about photosynthesis and food for plants might be enacted at the fifth-grade level in each of these paradigms. In describing units taught in a traditional didactic manner, in an inquiry mode, and in a conceptual change approach, I will describe existing materials and/or their use by teachers involved in my own research studies. Because curriculum materials with a science-technology-society organization are not yet available at the elementary level, I will describe a hypothetical unit in the STS tradition.

Teaching About Photosynthesis From Existing Textbooks--A Didactic Approach

In the most widely used elementary science textbook (Silver Burdett & Ginn's Science, Mallinson, et al., 1989), fifth graders learn about photosynthesis in a chapter about "Activities of Green Plants." Photosynthesis is included in the curriculum because it is one of several important activities of green plants, and this chapter presents a smorgasbord of information about activities of green plants. In a chapter that is divided into five lessons, students learn about: life processes (similarities and differences between plants and animals; cells; needs for food, releasing energy, removing wastes, growing, reproducing); 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.

The idea that plants make food is first suggested in lesson one. In Lesson 3 the word photosynthesis is given, and the cell structure of leaves where photosynthesis occurs is described. Then five steps in the photosynthetic process are listed, and a summary of the process is provided in a word equation (water + carbon dioxide + energy (from sunlight) --> sugar + oxygen). The directions to the teacher for this lesson on photosynthesis suggest an instructional pattern of reading the text and posing questions to "evaluate student understanding." The questions suggested in Lesson 3 to assess such understanding can all be answered in short phrases that are taken directly from the text passage:

> What does a plant need to make food? (water, carbon dioxide, light energy)
>
> How do materials needed to make food get to a green plant? (transported by root, stems, leaves)
>
> Where does the energy for green plants to make food come from? (sunlight)
>
> What is the name of the process by which green plants make food? (photosynthesis). (Mallinson et al., 1989, p. 12)

Suggested enrichment activities are to look at leaf cells under a microscope (student task is to draw cells and label the chloroplasts) and to cover a few leaves of a healthy green plant for one to two weeks (student task is to describe observations about the color and conditions of the covered leaves). In this lesson on photosynthesis, students read a lot of information and are expected to reproduce it in small bits when prompted by teacher questions. Only in a review question at the end of the lesson are students asked a question that requires them to explain anything (How do green plants make food?). The lesson does not include any application questions that require students to use photosynthesis to explain everyday observations or even to explain the observations in the enrichment activities. After the fact-focused lessons, the text presents a lesson on respiration followed by a lesson on reproduction. On that note the chapter ends, with assessment questions in the chapter review and chapter checkup again requiring students primarily to recall facts about plants:

> Write the correct term for each number in the diagrams (of a seed and a flower).
>
> Write the letter of the term that best matches the definition (chloroplast, embryo, vein, cell, seed, stamen, stomata, ovule, root hair, chlorophyll).

> Write the terms that are not required for respiration to occur. Use the remaining terms to describe this process (light energy, carbon dioxide, pistil, sugar, seed, oxygen). [Mallinson et al., 1989, pp. 24-25]

In a final section of the chapter review, four application-type questions are posed. Of the four "Thinking Like a Scientist" questions for this chapter, only one relates to photosynthesis: How are plants that grow underwater similar and different from land plants? This is the only question in the chapter that requires students to integrate their understandings about plant activities and to go beyond recalling facts that are clearly spelled out in the text.

This chapter does provide teachers with a series of manageable lessons but this sequence of lessons does not provide a coherent, focused instructional model that is likely to foster conceptual understanding and higher level thinking. Instead, instruction is a parade of two-page lessons in which the text (and teacher) show and tell students "all about" plants. Lessons are relatively isolated segments, much like the various acts and bands that follow one another in a parade. And this parade marches along at a brisk pace, inundating observers (students) with a panoply of facts and concepts to be absorbed. Students learn by reading and listening (watching the parade) and trying to mimic the performance of the teacher when questions are posed to them.

The role of the teacher that this text assumes is one of content authority and evaluator. The text and the teacher construct the "story" of photosynthesis as a sequence of facts and steps. The teacher monitors students' reading of this story by posing frequent short-answer, factual questions. Essentially, classroom discourse consists of students filling in the blanks in the textbook's and the teacher's "story." Experimental evidence to support or develop these stories is minimal. Higher level thinking of any kind is limited to a set of questions tucked away at the end-of-the-chapter review.

The view of science that students would most likely get from this didactic approach is as a large body of isolated, detailed facts and big words. The spirit of inquiry, puzzlement, debate, and sense-making that characterizes science is missing in these text pages. Students are assumed to "understand" photosynthesis if they can define it and identify where it takes place.

Teaching About Photosynthesis From an Inquiry Approach

Photosynthesis is included in the fifth grade SCIIS Communities Teacher's Guide (Knott, Lawson, Karplus, Thier, & Montgomery, 1978) for two important reasons: To build student understanding of a central concept in biology (the concept of plants as producers) and to teach students important science process skills. 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 (the cotyledon).

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 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. Much of Ms. Kain's planning time centered on the management details involved in pulling off all these activities smoothly. Discussions were also important aspects of lessons. Ms. Kain's questions focused on eliciting students' observations and explanations.

In this classroom discourse, the teacher played a supportive rather than evaluative role. She encouraged students to think about their observations and to generate possible explanations for these observations. She rarely gave out information (she explained photosynthesis only once during the unit and did not mention it again until the unit review). Nor did she give evaluative feedback to students to indicate which kinds of thinking were more appropriate and useful. She listened to students' ideas, sometimes repeated ideas, and then moved on, asking for other ideas or changing to new questions. Although the quality of students' ideas varied, all were received with equal receptiveness by Ms. Kain. She praised them for having interesting explanations but did not probe or challenge the adequacy of those explanations. Thus, Ms. Kain created many opportunities and a safe environment for students to explain observed phenomena; she never drilled students about definitions or details of the photosynthesis process. She spent eight weeks exploring photosynthesis with her students (approximately 24 lessons), quite a contrast with the one-lesson coverage of the Silver Burdett textbook.

And what did the students learn? Our posttests (Roth, Smith, & Anderson, 1983) focused on students' conceptual understanding by asking a variety of questions about how plants get their food. Only 11% of the students reorganized their entering conceptions that plants have multiple sources of food and ended the unit understanding that plants get their food only by making it themselves.

The rest clung to a variety of personal explanations (such as plants' getting food from the soil) as frameworks for explaining their observations. For example, many students' interpretation of the grass plants' dying in the dark was merely that plants need light to grow, an idea most of them believed prior to instruction. They did not, as intended, use the concept of photosynthesis to explain the experimental results.

Although students' conceptual learning was disappointing, students also had opportunities to learn about the nature of scientific inquiry, scientific processes, and scientific attitudes. What was learned in that arena? As suggested earlier with the case of Rachel (p. 44), many students were unclear why they were doing so much measuring and graphing. Science was fun because you get to do things but the meaning of that doing was unclear to many students. Students may have learned important procedures for graphing data, but most students did not use that graphing skill to improve their understanding about plants.

The instructional model embedded in this SCIIS unit was described in Ms. Kain's teachers's guide as focused around a learning cycle (Knott et al., 1978). The learning/teaching model has three phases: exploration, invention, and discovery. During exploration, children explore materials with minimal teacher guidance in the form of instruction or questions. The rationale for this phase is that "children learn about something through their own spontaneous handling and experimenting with objects to see what happens." (Knott et al., p. xviii). The teacher's role is to observe the children and draw conclusions about their existing ideas and understandings. Invention provides children with new concepts with which to interpret observations. The teacher provides definitions and terms to children. However, more experiences with concepts are need before students will understand and be able to sue the concepts.

In the discovery phase, a child "finds a new application of a concept through experience" (p. xviii). Discovery activities strengthen understanding of the concepts. The teacher's role is to engage students with the materials so that they can see how concepts apply. The teacher monitors small groups, asking questions to spur further investigation and reexplaining concepts where necessary. During discovery activities, concepts already introduced can be reinvented and also lead to exploration of the next concept.

This was a manageable model for Ms. Kain but not one that produced conceptual understanding and useful views of science among her students. Analysis of Ms. Kain's teaching of this unit over a three-year period helped us understand the limits of this model. Ms. Kain understood and implemented effectively the exploration phase of the cycle. However, the model did not help her appreciate how difficult it would be to help change their ideas and develop deeper understandings during the discovery phase. The model did not provide Ms. Kain (or other teachers in our study) with the support needed to develop such understandings. The model emphasizes student activity and construction of meaning, minimizing the teacher role as much as possible. While this approach has much potential to promote meaningful learning, the model communicates to teachers that understanding will grow out of students' interactions with materials (that "process" leads to conceptual understanding). Teachers were surprised that the conceptions students brought with them to class did not change as a result of their discovery activities.

Learning About Photosynthesis From a Science-Technology-Society Perspective

A science-technology-society unit would not focus on photosynthesis primarily because of its importance in the discipline or because of its power in helping students understand how scientists use scientific processes to construct explanations and theories. 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, the changing balance of O_2-CO_2 in earth's atmosphere due to the widespread use of fossil fuels, and the changing balance of O_2-CO_2 in earth's atmosphere due to widespread cutting of rain forests (plants use carbon dioxide in the photosynthesis 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 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 would focus on role playing and looking at the problems from different points of view. Scientific processes would be investigated in the context of assessing the evidence that the greenhouse effect is actually a danger. Students could 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 in these issues. Examples of such projects include:

1. Writing and circulating a pamphlet about ways to reduce energy consumption in the home.
2. Studying home gas and electric bills and trying to decrease consumption for a month.
3. Doing research to find out about home appliances that use particularly high amounts of energy to operate; brainstorming ways to make such appliances more energy-efficient.

4. Writing to state or national congressmen in support of particular bills related to energy issues.

5. Planting trees on school grounds and encouraging others to plant trees.

Higher level thinking in this unit would focus on understanding enough about photosynthesis and the atmosphere to be able to use that information in the decision-making process. Students would be engaged in rather 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.

The role of the teacher in this unit would be to guide students' developing understanding of relevant science concepts and the use of those concepts in addressing social problems. Attention would also be paid to helping students understand scientific processes so that they could at some level evaluate the reasonableness of scientists' predictions. Although we do not have models of such teaching in the research literature, it seems that 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.

For such teaching to be successful in addressing the larger goal of creating scientifically literate citizens, the unit would have to help students understand that knowledge of science concepts can enable better decision-making so that they would be good consumers of scientific knowledge. If students are to value this process, instruction must help them understand both the complexity of the problem (and the lack of easy answers) and the possibility that individual citizens can contribute to the solution of the problem. This creates a very demanding, conceptually complex role for the teacher.

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 or on the nature of chemical change. 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 than to remember that plants use up large amounts of atmospheric carbon dioxide in the process of 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.

Learning About Photosynthesis From a Conceptual Change Perspective

Recently, I taught my fifth-grade students about photosynthesis, using a modified version of curriculum materials I had written and evaluated in two earlier research studies (Roth, 1985b; Roth & Anderson, 1987). The materials were designed to help students change their entering conceptions of how plants get their food and to develop a useful understanding of photosynthesis. Photosynthesis was taught as a first step in helping students learn about ecological interactions and about changes in energy and matter. Instruction was organized around a modified version of Posner et al.'s (1982) conceptual change model:

1. Establish a problem by
    a. Eliciting students' ideas/explanations and encouraging discussion and debate among students.
    b. Challenging students' conceptions (creating dissatisfaction) using appropriate activities (experiments, demonstrations, discrepant events, discussions) and explanations.
    c. Presenting explanations of key concepts that will help resolve the problem and that make sense from the students' entering perspectives;
    d. Contrasting scientific explanations with students' personal explanations.
2. Provide numerous opportunities for students to apply new concepts to explain real-world, everyday phenomena. At first students' personal conceptions will persist as they work on these questions and tasks. The teacher, therefore, must play the role of "cognitive coach" (Collins, Brown, & Newman, 1987), helping students develop better strategies for comprehending concepts and explaining phenomena by:
    a. Modeling and coaching students through scaffolded tasks and dialogue.
    b. Fading amount of teacher support by engaging students that leads to independent use of scientific knowledge and integration with other scientific knowledge (from prior instruction and in future instruction).

A key piece of this model is the creation of a classroom learning community in which teacher and students are working together to develop and use scientific knowledge. To create this environment, the problem needs to be both scientifically significant and "real" to the students. In addition, both teacher and students need to listen to others' ideas seriously without accepting them uncritically. Meaningful conceptual change is fostered in a climate of sense making in which both students and teacher can raise questions and challenge and respond to others' ideas in ways that reflect serious and respectful attention and a concern for everyone's learning. Such dialogues provide a context where teachers can coach students and students can coach each other as they use new ideas.

A second critical feature ˜ the model is students' active engagement and construction of meaning and the teacher's role in supporting students' constructing of meaning. The model fosters active student thinking at each stage but also offers the students support (through modeling and scaffolded dialogues) to help them change and refine their entering conceptions in ways that are personally satisfying. In order to promote such active work by all students, instructional tasks often engage students in generating, defending, and debating predictions and explanations in small groups or pairs as well as in whole-class discussions. To foster students' meaningful engagement in tasks, the tasks at first require heavy teacher scaffolding. Over time and repeated opportunities to work with new concepts, students gradually can engage in application and problem-solving task without such heavy scaffolding.

Finally, the model provides for students' integration of concepts over time by building bridges from one instructional unit to the next. In my own teaching example, photosynthesis built on concepts of structure and function discussed in an earlier unit, were revisited as part of instruction about human body systems and cell respiration and were revisited again as part of the students' study of ecosystems and chemical change.

The unit began by asking students to write and talk about definitions of the word "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 <u>plants</u> or that rain water has energy in it even if drinking water does not. The class made a chart listing each of 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 an historical experiment provided initial information to help students puzzle through the problem of how plants get their food and how plants get their food in ways that are similar/different from humans. An experiment with germinating seed parts suggested that young plant embryos get food that is stored in the seed's cotyledon. Many students had predicted that the seed's embryo would grow if it were simply given water. They were surprised to learn that the embryo had to be attached to the cotyledon in order to grow. 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 either light or 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 investigated. Students made predictions that 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, in fact, the soil in von Helmont's experiment lost only a negligible amount of weight, for the most part, they accepted this as convincing evidence that soil was not food for plants. 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 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 <u>alone</u> 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?

At this point most of the students' entering ideas about food for plants had been either ruled out or brought into question. This was when an explanation of photosynthesis was given: That cells in plants' leaves use light energy from the sun to change water and air into energy-containing food. Once this idea was explained and explored in contrast with students' entering ideas, students were given many opportunities to use this idea to explain everyday phenomena. In addition, their own application questions were rewarded and encouraged. One student, for example, wondered about the fact that <u>only</u> green 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.

Application opportunities also included teacher-given problems posed in overhead transparencies, questions posed for students to write and/or talk about, and further experimentation. Students also wrote in science log books about their evolving ideas and received 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 relationship among ideas were also used. The applications provided feedback for me about student understanding; they enabled students to develop deeper understandings as they attempted to work through them individually, in pairs or small groups, and in whole class discussions. Modeling and coaching was provided both by my written comments to students and by my dialogue with students. It was also provided by <u>students</u> in their small-group work and in their efforts to teach each other in the whole class setting.

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 posttest 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.

The teacher's role in this kind of instruction changes from day to day. Initially, the teacher serves as a sounding board for students' ideas, helping them clarify their own explanations. At other times the teacher uses careful questioning strategies, gives feedback that challenges students to rethink their ideas, and points out contrasts between their ideas. At other times, the teacher presents and explains scientific terms and concepts. At all times, the teacher is listening carefully to students' ideas, trying to make instruction be responsive to students' thinking. During the application phase the teacher moves from modeling good responses to heavily scaffolding and coaching students' efforts to apply ideas. The goal is to fade the teacher's structure and support gradually in students' application efforts. However, throughout the unit the teacher's role is to stimulate student thinking and to involve students actively in working through ideas. In the photosynthesis unit, this involved providing numerous occasions for students to write about their developing ideas, to talk about ideas in pairs, small groups, and in the whole group, and to raise questions.

This unit involved much more time than the one lesson on photosynthesis outlined in the Silver Burdett text (Mallinson et al., 1989). And yet the unit did not present many of the technical terms covered in the Silver Burdett lesson--chloroplasts, stomata, carbon dioxide, hydrogen. 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 improve their understandings and their abilities to explain and apply ideas. The instructional model proved both workable for me and productive of meaningful conceptual understanding of my students. Although it did not call for explicit teaching of science processes, students regularly used these processes in constructing their developing understandings. Although it did not involve exploration of societal issues, it did provide a base for a later study of the cutting down of rain forests explored after a unit on ecosystems.

Relationships Among the Three Perspectives and Current Practice: What's Feasible?

Each of the three perspectives explored in this paper emphasizes teaching students to think scientifically in much richer ways than being able to recall scientific facts. Each perspective suggests instructional strategies that will engage students more actively in scientific thinking, and each criticizes didactic approaches to science teaching as failing to help students develop meaningful understanding of the nature of science and scientific thinking. But such didactic approaches to elementary science teaching are embedded in the mostly widely used curriculum materials and characterize much of existing science instruction. Why is the existing curriculum so strikingly different from the experts' visions?

It is important to consider the reasons why textbook-bound, fact-oriented didactic approaches to elementary science teaching continue to dominate despite clear evidence that such instruction is not meaningful for the majority of students. If recommendations about the elementary science curriculum are going to become realizable statements of goals rather than idealistic wishes and hopes, the constraints facing elementary teachers must be understood and seriously considered when formulating goals and desired outcomes. In this section, I suggest two significant barriers to elementary science instruction that promotes conceptual understanding, critical thinking, and dispositions to engage in scientific inquiry: (a) the time and planning demands that teachers face and (b) the knowledge required to teach students to do scientific thinking that goes beyond rote memorization.

The Problem of Time

A critical constraint that elementary teachers face in teaching science is time. Time is a problem in several ways. First, science is often squeezed out of the school day due to pressures to teach the basics (reading, spelling, writing, grammar, mathematics) and all the other curricular demands (art, music, literature, social studies, physical education, health, sex education, special projects in drama and community service, pull-out programs for special needs children, instrumental music, etc.). Science is typically scheduled for afternoon times, and as the day progresses its scheduled time is often eaten away by other priorities, leaving even less time for instruction than was planned.

Time is an even more serious problem in terms of teacher planning time. Teaching photosynthesis from any of the three perspectives described above requires careful planning of materials, of grouping arrangements, of assignments and tasks, and of classroom discussions. If students are going to do more extensive writing than the fact-oriented, short answers required in standard textbook teaching, teachers need time to read and respond to this writing. When teachers are planning for five or more subjects daily, they do not have time to spend extended blocks of time preparing for science lessons alone. Add to this the fact that, unlike secondary teachers, elementary teachers are not typically guaranteed a daily planning hour and the time for planning becomes even more critical. If teachers are going to tailor instruction to students' developing understandings rather than to a page number in the textbook, teachers need time to reflect seriously on their instruction and their students' thinking. Current workload expectations force teachers to pay lip service to such quality in their planning. In reality, time pressures do not permit thoughtful, analytic planning.

Finally, time is a problem because each of these three perspectives requires that teachers spend considerable time on a given unit or concept in order to develop meaningful conceptual understandings, decision-making skill, or understandings of scientific approaches to inquiry, but textbooks and state and local curriculum guidelines include long lists of topics and objectives to be covered. Whether or not teachers are held closely to these lists by administrators, teachers feel driven by them to cover material at a quick pace. In my own teaching experience, I remember patting myself on the back when I got further through the textbook than my peers or than in my previous year's experience. If covering content in depth is to be valued, teachers need the support of realistic expectations in curricular guidelines.

Teacher Knowledge

Although some experts argue that teachers can teach science effectively by learning right along with their students (Duckworth, in press; Easley, in press), my studies of the role of teachers' knowledge in science teaching suggest that teachers' effectiveness in promoting rich conceptual understandings of science is facilitated when teachers have particular kinds of knowledge about science, about learners, and about how learners best come to understand science (Roth, 1987). Teachers' effectiveness in helping students develop understandings that they can use to explain a variety of phenomena is enhanced when they have both well structured and functional understandings of the science topic. Understandings of the structure of scientific knowledge in the domain (the various ways in which scientists organize, relate, and integrate ideas) and the usefulness of the knowledge (functions) in explaining everyday phenomena that are in students' experiences are particularly important. Teachers also need to go beyond understanding scientific thinking as just a logical set of steps from observation to conclusion. If they are going to engage students in genuine inquiry and problem solving, they need to understand science as a creative, sense-making endeavor in which evidence can be drawn from a variety of sources, points of view can be argued, answers change as evidence and arguments accumulate, and a questioning, skeptical stance is valued.

In conjunction with these understandings of particular concepts and of the nature of science, teachers are more effective in teaching for conceptual understanding if they also understand how students' thinking about particular topics or concepts develops: What ideas are particularly problematic for students? What misconceptions do students hold that pose barriers to their understanding of scientific explanations? What kinds of questions do students typically have? Teachers need knowledge about how students make sense of particular concepts at different developmental stages. They also need to know how to connect their students' conceptions and questions with scientific concepts and ways of thinking.

Teachers also benefit when they are able to learn from their own teaching and from their students. To do this requires an analytical stance toward teaching, in which teachers do not interpret students' learning failures as a personal threat or as student laziness but draw from the thinking that students *are* doing to analyze appropriate next steps in instruction. Such reflective teaching practice is not a part of the professional milieu in most elementary schools; this is partly related to the time constraints issue but also represents a lack of knowledge. Most teachers have not had the opportunity to learn how to analyze their teaching in this way.

In sum, teaching for understanding is supported by rich teacher knowledge of the structure and functions of particular topics in the science curriculum, of the nature of science as a discipline, of students' ways of thinking and learning about natural phenomena, and of analytical frameworks for learning from one's own teaching experience. In reality, however, elementary teachers have limited backgrounds in science. Even worse, the science courses they have taken did not model science as sense making. Science courses teachers take are typically taught in didactic, authoritative ways emphasizing detailed knowledge of specialized abstract cycles, formulas, structures, and principles rather than functional understandings of how these cycles, formula, structures, and principles can explain everyday phenomena in children's (and adults'!) experiences (how plants get their food, how and why we sweat, why we can see through some objects and not others, why it snows, why bicycles rust, why it's easier to ride a bike uphill in "low gear", etc.) [Roth, 1989]. Because of their limited subject matter knowledge, teachers often lack the confidence to teach science and are reluctant to open up discussion for fear that their authority as an expert will be challenged. Because teachers do not open up discussions but instead search for "correct" answers to the limited questions typically posed in science textbooks, they miss opportunities to engage students actively in understanding science and to learn about their students' ways of thinking and understanding.

Finally, professional development in both inservice and preservice education typically does not foster the development of dispositions and skills for reflective inquiry about one's own teaching practice. Instead, inservice workshops are too often short shots of ideas and activities to try right away. These "make and take" science workshops that teachers find enjoyable and immediately useful do not foster long-term growth or promote teaching for understanding. Teachers have not had opportunities to learn how longer term efforts to study their own teaching can promote more meaningful changes and understandings. In the current school climate such an approach to inservice teacher education would constitute a dramatic shift in expectations of the purposes and structure of inservice teacher education.

Summary

There are very real, important constraints that make it difficult for most elementary teachers to teach for conceptual understanding, for problem solving and decision making, or for inquiry-process thinking. Time and teacher knowledge are two critical constraints that need to be seriously considered in experts' attempts to outline realizable, desired outcomes of elementary science instruction.

Personal Perspectives and Quandaries

In this paper, I have stressed the need for providing teachers with a framework or model for thinking about science teaching. It is my contention that teachers' understanding of such a framework will better enable them to promote good scientific thinking (conceptual understanding, problem-solving, inquiry) than long lists of goals and objectives that are either ignored or are checked off as they are "covered."

Currently I am conducting a research project in which I am exploring the possibilities and limitations of a conceptual change perspective to provide such a workable and powerful model. To study these issues I am teaching fifth-grade science from a conceptual change orientation. I am studying both the impact of such teaching on student learning across a school year and the kinds of supports and knowledge needed to teach effectively using this model. I am using a conceptual change framework for selecting content, in planning, and in teaching, in assessing student learning. What is possible in terms of student learning when this one perspective is selected for focus? What pieces of the inquiry and STS perspectives get incorporated into my teaching and my student's learning? What important pieces of the other perspectives get left out? What are the consequences for students?

A Workable Model for Teachers

As I plan lessons and teach my fifth graders, I do not have long lists of "higher level" goals and process thinking skills in mind. Instead, using a conceptual change perspective, I focus on helping students genuinely make sense of important, central concepts of science. Making sense of concepts requires that students be able to relate these concepts to their personal ideas, that they see how these concepts can help them make better sense of experiences around them, and that they gradually begin to link scientific concepts together. The conceptual change model referred to earlier has proved a useful framework in keeping this overall goal in focus.

In selecting content to be covered, for example, I think about changes in student understanding: What concepts and topics could students come to understand in deeper ways? How could concepts studied across the school year be integrated to contribute to students' deepening understandings? I consider what I know about students' thinking to make such decisions: What kind of understanding/misconceptions do fifth-grade students typically have about particular concepts? What views of scientific thinking do they have? What events in their experience would intrigue them to understand? What kinds of things are they curious about? In planning and teaching I keep in mind a conceptual change model for selecting, monitoring, and evaluating student tasks. The questions that guide my ongoing decision making are: How are students making sense of this? What are their conceptions? What classroom activity will be most supportive of helping them think about x or y in new and more powerful ways?

Using this conceptual change framework, I do not *plan* to teach specific process skills. However, in analyzing my teaching post hoc, I can "check off" the lists of higher level goals or process skills that my students have engaged in. They are frequently engaged, for example, in predicting, hypothesizing, inferring, raising questions, analyzing, and synthesizing ideas. They are often involved in metacognitive activities--analyzing the gaps in their own knowledge, identifying ideas that are confusing, asking clarification questions. However, my measure of success is not that students have engaged in these thinking skills but in how well the students understand the concepts, can apply them, and can raise thoughtful questions about them. Did all the "thinking skills" lead anywhere? Thus, the conceptual change model frees me as a teacher from overwhelming lists of isolated thinking skills that I need to monitor. It provides a framework that helps me integrate those thinking skills in teaching for meaningful understanding.

I also do not specifically plan to address science-technology-society goals. However, analysis of my teaching reveals that such goals are addressed as a natural part of conceptual change teaching. Using a conceptual change orientation, I am constantly trying to help students link their experiences to the science concepts I am teaching. Technology, society, and health issues come up in this context. For example, my students (after much work) changed their conception that food taken into the body does not just go in the body, through the digestive system, and out of the body (the concept they brought with them after an extensive fourth-grade health unit on digestion). Instead, they came to understand that food and other ingested materials end up in the bloodstream and travel to all cells in the body.

This led to a series of concerned student questions and observations such as Bob's: "My Mom smoked and drank when she was pregnant with me; is that why I'm short?" This unit also led to student requests to do a frog dissection. This request provided an occasion for a series of discussions about the use of animals in research and a consideration of when new technologies might provide alternatives to animal testing. I had a university researcher in biology visit the class to help students consider this science-technology-society issue. Students engaged in informed decision-making about whether or not to do a frog dissection.

There are certainly important pieces of the inquiry and STS perspectives that were not addressed in my teaching, and I am currently analyzing student learning to assess the consequences of such omissions. For example, I did not do much explicit teaching about either controlled experimentation or graphing of data. I also did not "fade" my scaffolding of student application work to the point of providing more open-ended, complex, and less structured problem-solving tasks. However, I am convinced that this model enabled me to manage the complex task of helping 29 fifth graders undergo significant changes in their understandings of particular science concepts, in their ways of thinking and in their dispositions to inquire and make sense. Thus, the conceptual change model helped me define and achieve meaningful, selected goals for elementary science teaching.

Can this model be equally useful for teachers who lack my personal background and interest in science? What kinds of support would teachers need to teach for conceptual change? For this approach to be feasible teachers need new kinds of curriculum materials to support them well as school structures and curriculum guidelines that pay more than lip service to the goal of teaching for conceptual understanding. Elementary teachers cannot be truly thoughtful about their work as long as they must work with inadequate textbooks and must plan and teach five or more preparations each day. Careful curricular development done hand-in-hand with research on student learning is a critical need. However, even such curriculum development efforts are likely to fail unless teachers' work is restructured to give them time to be thoughtful and reflective.

Meaningful Learning for Students

My enthusiasm for a conceptual change perspective stems primarily from its impact on student learning. A conceptual change perspective puts the focus on how students learn and what students understand. Both didactic and inquiry orientations to teaching have focused too much on what scientists know and do. The conceptual change perspective reflects a richer view of the nature of science, avoiding a lopsided emphasis on either science process skills or science content. The emphasis on applications gives students opportunities to use scientific knowledge, not just to learn how new scientific knowledge is created.

This richer, more meaningful understanding of science seems likely to help students develop important scientific attitudes and dispositions. One change I have observed in my fifth-grade students is their increased willingness, eagerness, and ability to ask thoughtful questions. These questions reflect a disposition to inquire, to puzzle about things, and to link ideas together to make better sense of the world. This disposition may perhaps be the critical outcome of elementary science education. While students may <u>like</u> science in an inquiry perspective because of all the activities, or they may enjoy science in STS perspective because they talk about relevant issues, there is a difference between liking science and developing the disposition to inquire in meaningful ways. The development of such a disposition is not always recognized as fun or enjoyable. And such dispositions do not necessarily grow out of fun activities. Rather, they grow out of careful learning about what it means to really understand something and about the nature of good, scientific explanations. Students need to appreciate the way in which understanding and knowledge are not only ends; they are also gates that allow them to ask new and important questions.

In my unit on photosynthesis, I was impressed by the improvement in the quality and quantity of my students' questions once they had begun to make real sense of photosynthesis. I hope that they, too, were excited by their own questions and will appreciate that understanding is worth struggling for not only because it <u>answers</u> questions but also because it leads to new and more interesting questions. A conceptual change perspective seems to me to have the potential to help the majority of students develop the conceptual understanding that will foster dispositions to make sense, to puzzle, and to inquire.

References

Abruscato, J., Hassard, J., Fossaceca, J. W., & Peck, D. (1984). Science. New York: Holt, Rinehart & Winston.

American Association for the Advancement of Science. (1989). Science for All Americans (A Project 2061 Report). Washington, DC: Author.

American Association for the Advancement of Science. (1970). Science--A Process Approach. Commentary for teachers. Lexington, MA: Ginn.

Anderson, C. W. (1987, October). Incorporating recent research on learning into the process of science curriculum development (Commissioned paper for the IBM-supported Design Project). Colorado Springs, CO: Biological Sciences Curriculum Study.

Anderson, C. W. (1988, October). Assessing student understanding of biological concepts. Presented at the national invitational conference, High School Biology Today and Tomorrow, Washington, DC.

Anderson, C. W., Belt, B. L., Gamalski, J. M., & Greminger, J. (1987). A social constructivist analysis of science classroom teaching. In J. Novak (Ed.). Proceedings of the second international seminar on misconceptions and educational strategies in science and mathematics (Vol. 1, pp. 11-24). Ithaca, NY: Cornell University Press.

Anderson, C. W., & Roth, K. J. (in press). Teaching for meaningful and self-regulated learning of science. In J. Brophy (Ed.) Advances in research on teaching: Vol. 1. Teaching for meaningful understanding and self-regulated learning. Greenwich, CT: JAI Press.

Anderson, C. W., & Smith, E. L. (1983a, April). Children's conceptions of light and color: Developing the concept of unseen rays. Paper presented at the annual meeting of the American Educational Research Association, Montreal, Canada.

Anderson, C. W., & Smith, E. L. (1983b, April). Teacher behavior associated with conceptual learning in science. Paper presented at the annual meeting of the American Educational Research Association, Montreal, Canada.

Anderson, C. W., & Smith, E. L. (1987). Teaching science. In V. Richardson-Koehler (Ed.), Educators' handbook: A research perspective (pp. 104-111). New York: Longman.

Assessment of Performance Unit. (1983-87). Science reports for teachers, No. 1-8. Hatfield, England: Association for Science Education.

Ayers, J. B., & Ayers, M. N. (1973). Influence of SAPA on Kindergarten children's use of logic in problem solving. School Science and Mathematics, 73, 768-771.

Ayers, J. B, & Mason, G. E. (1969). Differential effects of science: A Process approach upon change in Metropolitan Reading Test scores among kindergarten children. Reading Teacher, 20, 435-9.

Baron, J. (1988). What we learn from state assessments of elementary school science. Paper presented at the Lesley College Assessment Planning Conference. Available from author, Connecticut Department of Education, Hartford, CT.

Bell, B. F. (1981). When is an animal not an animal? Journal of Biological Education, 15(3), 213-218.

Bethel, L. J. (1974). Science inquiry and the development of classification and oral communication skills in inner-city children. Unpublished doctoral dissertation, University of Pennsylvania, Philadelphia.

Biological Sciences Curriculum Study. (1988). Science for life and living: Integrating science, technology, and health. Experimental edition. Dubuque, IA: Kendall/Hunt.

Black, P. J. (1987). The school science curriculum: Principles for a framework. In A. B. Champagne and L. E. Hornig (Eds.), The science curriculum: The report of the 1986 National Forum for School Science (pp. 13-33). Washington, DC: American Association for the Advancement of Science.

Blakeslee, T., & Anderson, C. W. (1987, April). Teaching strategies associated with conceptual change in science learning. Paper presented at the annual meeting of the American Educational Research Association, Washington DC.

Bowyer, J. B., & Linn, M. C. (1978). Effectiveness of the Science Curriculum Improvement Study in teaching scientific literacy. Journal of Research in Science Teaching, 15, 209-219.

Bredderman, T. (1983). Effects of activity-based elementary science on student outcomes: A quantitative synthesis. Review of Educational Research, 53, 499-518.

Brook, A., & Driver, R. (1986). The construction of meaning and conceptual change in classroom settings: Case Study on Energy. Leeds, England: Centre for Studies in Science and Mathematics Education, Children's Learning in Science Project.

Bruner, J. S. (1963). The process of education. New York: Random House.

Bybee, R., & Landes, N. M. (1988). What research says about the new science curricula . . . The biological sciences curriculum study (BSCS). Science and Children, 25, 36-37.

Bybee, R., Peterson, R., Bowyer, J., & Butts, D. (1984). Teaching about science and society: Activities for elementary and junior high school. Columbus, OH: Charles E. Merrill.

Bybee, R. W. (1987). Science education and the science-technology-society (S-T-S) theme. Science Education, 71(5), 667-683.

Bybee, R. W. (1988). Contemporary elementary school science: The evolution of teachers and teaching. In A. B. Champagne (Ed.), Science teaching: Making the system work (pp. 153-171). Washington, DC: American Association for the Advancement of Science.

Bybee, R. W., Buchwald, C. E., Crissman, S., Heil, D., Kuerbis, P. J., Matsumoto, C., & McInerney, J. D. (1989). Science and technology education for the elementary years: Frameworks for curriculum and instruction. Andover, MA: National Center for Improving Science Education.

Caplon, J. (1988). Science and the liberal arts. A presentation to a panel of the American Association of the Advancement of Science.

Carey, S. (1986). Cognitive science and science education. American Psychologist, 41, 1123-1130.

Carin, A. A., & Sund, R. B. (1980). Teaching science through discovery. Columbus, OH: Merrill.

Carrick, T. (1987). Reflections on practical assessment in GCSE 2: Implementation and implications of GCSE requirements. Journal of Biological Education, 21(3), 167-174.

Champagne, A. B., Gunstone, R. F., & Klopfer, L. E. (1983, April). Effecting changes in cognitive structure among physics students. Paper presented at symposium on Stability and Change in Conceptual Understanding at the annual meeting of American Educational Research Association, Montreal, Canada.

Champagne, A. B., & Hornig, L. E. (1987). Critical questions and tentative answers for the school science curriculum. In A. B. Champagne and L. E. Hornig (Eds.), The Science Curriculum: The Report of the 1986 National Forum for School Science (pp. 1-12). Washington, DC: American Association for the Advancement of Science.

Champagne, A. B., & Klopfer, L. E. (1984). Research in science education: The cognitive psychology perspective. Reprinted from D. Holdzom & P. B. Lutz (Eds.), Research within reach: Science education (pp. 171-189). Charleston, WV: Appalachia Educational Laboratory, Research and Development Interpretation Service.

Champagne, A. B., Klopfer, L. E., & Anderson, J. H. (1980). Factors influencing the learning of classical mechanics. American Journal of Physics, 48, 1074-1079.

Champagne, A. B., Klopfer, L. E., & Gunstone, R. F. (1982). Cognitive research and the design of science instruction. Educational Psychologist, 17, 13-53.

Champagne, A. B., Klopfer, L. E., Solomon, C. A., & Cahn, A. D. (1980). Interactions of students' knowledge with their comprehension and design of science experiments (LRDC Publication 1980/9). Pittsburgh: University of Pittsburgh, Learning Research and Development Center.

Chi, M. T. H., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. Cognitive Science, 5, 121-152.

Chi, M. T. H., Glaser, R., & Rees, E. (1982). Expertise in problem solving. In R. Sternberg (Ed.), Advances in the psychology of human intelligence (Vol. 12, pp. 7-75). Hillsdale, NJ: Erlbaum.

Chittenden, E. (1984). Interim report: Committee for assessment in science education. Princeton, NJ: Educational Testing Service.

Chittenden, E. (1988). Young children's discussion of science topics: Implications for assessment and instruction. Paper presented at the Lesley College Assessment Planning Conference. Available from author, Educational Testing Service, Princeton, NJ.

Clement, J. (1982). Students' preconceptions in introductory mechanics. American Journal of Physics, 50(1), 66-71.

Coble, C. R., & Rice, D. R. (1982). A project to promote elementary science in North Carolina, Part II. School Science and Mathematics, 82(2), 148-156.

Commission on Science Education. (1970). Commentary for teachers--Science: A process approach. Washington, DC: American Association for the Advancement of Science.

DiSessa, A. A. (1982). On learning Aristotelian physics: A study of knowledge-based learning. Cognitive Science, 6, 37-75.

DiSessa, A. A., & Ploger, D. (1987). Cognition and science education. In Champagne & Hornig (Eds.), Students and science learning (pp. 15-39). Washington, DC: American Association for the Advancement of Science.

Driver, R. (1983). The pupil as scientist? Milton Keynes, England: Open University Press.

Driver, R. (1987). Promoting conceptual change in classroom settings: The experience of the Children's Learning in Science Project. In J. D. Novak (Ed.), Proceedings of the Second International Seminar on Misconceptions and Educational Strategies in Science and Mathematics (pp. 97-110). Ithaca, NY: Cornell University.

Driver, R., Guesne, E., & Tiberghien, A. (1985). Children's ideas in science. Philadelphia: Open University Press.

Driver, R., & Oldham, V. (1986). A constructivist approach to curriculum development in science. Studies in Science Education, 13, 105-122.

Duckworth, E. (in press). Opening the world. In D. Trumbull (Ed.), *Teaching elementary school science: A minds-on approach*. Hillsdale, NJ: Erlbaum.

Easley, J. (in press). Elementary school science involving all children can be led by any teacher stressing dialogic skill. In D. Trumbull (Ed.), *Teaching elementary school science: A minds-on approach*. Hillsdale, NJ: Erlbaum.

Eaton, J. F., Anderson, C. W., & Smith, E. L. (1984). Students' misconceptions interfere with science learning: Case studies of fifth-grade students. *Elementary School Journal* *84*, 365-379.

Education Development Center. (1970). *Elementary Science Study teacher's guides*. New York: McGraw-Hill.

Educational Policies Commission. (1966). *Education and the spirit of science*. Washington, DC: National Education Association.

Edwards, C. H., & Fisher, R. L. (1977). *Teaching elementary school science: A competency-based approach*. New York: Praeger.

Ellis, A. K. (1977). The USMES approach to problem solving: An interview. *Social Education*, 411-413.

Erickson, G. L. (1979). Children's conceptions of heat and temperature. *Science Education*, *63*, 221-230.

Erickson, G. L. (1984, April). *Some issues on cognitive structure and cognitive change in science education: One perspective from North America*. Paper presented at a symposium on Cognitive Structure and Cognitive Change at the annual meeting of the American Educational Research Association, New Orleans.

Esler, W. K., & Esler, M. K. (1981). *Teaching elementary science*. Belmont, CA: Wadsworth.

Farmer, W. A., & Farrell, M. A. (1980). *Systematic instruction in science for the middle and high school years*. Reading, MA: Addison-Wesley.

Fensham, P. J. (1986-87). Science for all. *Educational Leadership*, *44*(4), 18-23.

Fulton, H. F. Gates, R. W. Krockover, G. H. (1980). An analysis of the teaching of science in the elementary school at this point in time: 1978-79. *School Science & Mathematics*, *80*, 691-702.

Gagné, R. M. (1965). *The psychological basis of science--A process approach*, (AAAS miscellaneous publication, 65-68). Washington, DC: American Association for the Advancement of Science.

Gilbert, J. K., & Watts, D. M. (1983). Concepts, misconceptions, and alternative conceptions: Changing perspectives in science education. *Studies in Science Education*, *10*, 61-98.

Glaser, R. (1984). Education and thinking: The role of knowledge. *American Psychologist*, *39*, 93-104.

Gunstone, F. G., and White, R. T. (1981). Understanding of gravity. *Science Education*, *65*, 291-299.

Harms, N. C. (1981). Project Synthesis: Summary and implications for teachers. In N. C. Harms & R. E. Yager (Eds.), *What research says to the science teacher* (pp. 113-127). Washington, DC: National Science Teachers Association.

Harms, N. C., & Kahl, S. (1981). *The status and needs of pre-college science education: Report of Project Synthesis*, (Final report to NSF for Grant SED-77-19001). Washington, DC: U.S. Government Printing Office.

Harms, N. C., & Yager, R. E. (1981). *What research says to the science teacher* (Vol. 3, No. 471-14776). Washington, DC: National Science Teachers Association.

Hawkins, D. (1965). Messing about in science. *Science and Children*, *2*(5), 5-9.

Helgeson, S. L., Blosser, P. E., & Howe, R. W. (1977). *The status of pre-college science, mathematics, and social science education, 1955-1975*. Washington, DC: U.S. Government Printing Office.

Helm, H., & Novak, I. D. (1983). *Proceedings of the international seminar on misconceptions in science and mathematics*. Ithaca, NY: Cornell University.

Henson, K., & Janke, D. (1984). *Elementary science methods*. New York: McGraw-Hill.

Hewson, P. W. (1983, April). *Microcomputers and conceptual change: The use of a microcomputer program to diagnose and remediate alternative conceptions of speed*. Paper presented at the annual meeting of the American Educational Research Association, Montreal, Canada.

Hewson, P. W., & Hewson, M. G. (1984). The role of conceptual conflict in conceptual change and the design of science instruction. *Instructional Science*, *13*, 1-13.

Hollon, R. E., Anderson, C. W., & Roth, K. J. (in press). Teachers' conceptions of science teaching and learning. In J. Brophy (Ed.), *Advances in research on teaching: Vol. 2. Teachers' subject-matter knowledge and classroom instruction*. Englewood Cliffs, NJ: JAI Press.

Horn, J. G., & James, R. K. (1981). Where are we in elementary science education? *School Science and Mathematics*, *81*, 205-214.

Hueftle, S. J., Rakow, S. J., & Welch, W. W. (1983). *Images of science: A summary of results from the 1981-82 National Assessment in Science*. Minneapolis: University of Minnesota, Minnesota Research and Evaluation Center.

Huff, P., & Languiss, M. (1973). The effects of the use of activities of SAPA on the oral communication skills of disadvantaged kindergarten children. Journal of Research in Science Teaching, 10, 165-73.

Hurd, P. (1986). Perspectives for the reform of science education. Phi Delta Kappan, 67, 353-358.

Jacobson, W. J., & Bergman, A. B. (1980). Science for children: A book for teachers. Englewood Cliffs, NJ: Prentice-Hall.

Johansson, B., Marton, F., & Svensson, L. (1985). An approach to describing learning as change between qualitatively different conceptions. In L. H. T. West and A. L. Pines (Eds.), Cognitive structure and conceptual change (pp. 233-257). Orlando: Academic Press.

Johnson, C. N., & Wellman, H. M. (1982). Children's developing conceptions of the mind and the brain. Child Development, 53, 222-234.

Kessen, W. (1970). Statement of purposes and objectives of science education in school. In Science--A process approach, commentary for teachers (pp. 3-7). Washington DC: American Association for the Advancement of Science.

Knott, R., Lawson, C., Karplus, R., Their, H., & Montgomery, M. (1978). SCIIS communities teacher's guide. Chicago: Rand McNally.

Kuhn, D. (1986). Education for thinking. Teachers College Record, 87, 495-512.

Kuhn, K., & Aguirre, J. (1987). A case study--on the "journal method"--A method designed to enable the implementation of constructivist teaching in the classroom. In J. D. Novak (Ed.), Proceedings of the second International Seminar on Misconceptions and Educational Strategies in Science and Mathematics (pp. 262-274). Ithaca, NY: Cornell University.

Larkin, J., McDermott, J., Simon, D. P., & Simon, H. A. (1980a). Expert and novice performance in solving physics problems. Science, 208, 1335-1342.

Larkin, J. H., McDermott, J., Simon, D. P., & Simon, H. A. (1980b). Models of competence in solving physics problems. Cognitive Science, 4, 317-345.

Lawson, A. E., Nordland, F. H., & Kahle, J. B. (1975). Levels of intellectual development and reading ability in disadvantaged students and the teaching of science, Science Education, 59(1), 113-125.

Lawson, A. E. (1985). A review of research on formal reasoning and science teaching. Journal of Research in Science Teaching, 22, 569-618.

Lawson, A., Abraham, M., & Renner, J. (1989). A theory of instruction: Using the learning cycle to teach science concepts and thinking skills (National Association for Research in Science Teaching Monograph One). Cincinnati: NARST.

Leboutet-Barrel, L. (1976). Concepts of mechanics in young people. *Physics Education*, 11, 462-466.

Lee, O. (1989). *Motivation to learn science and conceptual understanding in middle school students*. Unpublished dissertation, Michigan State University.

Linn, M. C., & Thier, H. D. (1975). The effect of experiential science on development of logical thinking in children. *Journal of Research in Science Teaching*, *12*, 46-62.

Linn, M. C. (1987). Establishing a research base for science education: Challenges, trends, and recommendations. *Journal of Research in Science Teaching*, *24*, 191-216.

Linn, M. C. (1988). Science education and the challenge of technology. In J. Ellis (Ed.), *Informational technologies and science education* (1988 yearbook of the Association for the Education of Teachers in Science, pp. 119-144). Columbus, OH: ERIC Clearinghouse for Science, Mathematics, and Environmental Education.

Linn, M. C., & Peterson, R. W. (1973). The effect of direct experience with objects on middle class, culturally diverse, and visually impaired young children. *Journal of Research in Science Teaching*, *10*, 83-90.

Linn, M. C. & Songer, N. B. (1989, April). *Cognitive research and instruction: Incorporating technology into the science curriculum*. Paper presented at the annual meeting of the American Educational Research Association, New Orleans.

Linn, M. C. (in press). Science curriculum design: Views from a psychological framework. In R. Dillon & R. Sternberg (Eds.). *Psychology and curriculum design*. New York: Academic Press.

Mallinson, G. G., Mallinson, J. B., Valentino, C., & Smallwood, W. L. (1989). *Science*, Morristown, NJ: Silver Burdett & Ginn.

Marton, F., & Ramsden, P. (1988). What does it take to improve learning? In P. Ramsden (Ed.), *Improving earning* (pp. 1-35). London: Kogan Page.

McCloskey, M. (1983). Intuitive physics. *Scientific American*, *248*(4), 122-130.

Meyer, L., Crummey, L., & Greer, E. (1988). Elementary science textbooks: Their contents, characteristics, and comprehensibility. *Journal of Research in Science Teaching*, *25*, 435-64.

Millar, R., & Driver, R. (1987). Beyond processes. *Studies in Science Education*, *14*, 33-62.

Miller, J. K. (1986). *An analysis of science curricula in the United States* (Second IEA science study). New York: Teachers College.

Minstrell, J. (1982). Conceptual development research in the natural setting of the classroom. In M. Rowe (Ed.), *Education in the 80's: Science*. Washington DC: National Educational Association.

Minstrell, J. (1984). Teaching for the understanding of ideas: Forces on moving objects. In C. W. Anderson (Ed.), Observing science classrooms: Perspectives from research and practice (1984 yearbook of the Association for the Education of Teachers in Science, pp. 55-74). Columbus, OH: ERIC Center for Science, Mathematics, and Environmental Education.

Morgan, A., Rachelson, S., & Lloyd, B. (1977). Sciencing activities as contributors to the development of reading skills in first grade students. Science Education, 61, 135-144.

Mullis, I. V. S. (1987). The science report card: A description of the 1985-86 NAEP science assessment and the higher order skills assessment pilot study. In A. B. Champagne and L. E. Hornig (Eds.), The science curriculum: The report of the 1986 National Forum for School Science (pp. 107-125). Washington, DC: American Association for the Advancement of Science.

Mullis, I. V. S., & Jenkins, L. B. (1988). The science report card: Trends and achievement based on the 1986 National Assessment. Princeton, NJ: Educational Testing Service.

National Assessment of Educational Progress. (1978). Science achievement in the schools: A summary of results from the 1976-77 national assessment of science. Denver: Education Commission of the States.

National Assessment of Educational Progress. (1979a). Three assessments of science 1969-77: Technical summary. Washington, DC: National Center for Educational Statistics.

National Assessment of Educational Progress. (1979b). Attitudes toward science: A summary of results from the 1976-77 national assessment of science (Report No. 08-5-02). Denver: Education Commission of the States.

National Assessment of Educational Progress. (1987). Learning by doing: A manual for teaching and assessing higher order thinking in science and mathematics. Princeton, NJ: Educational Testing Service.

National Science Teachers Association. (1964). Theory into action in science curriculum development. Washington, DC: National Science Teachers Association.

National Science Teachers Association, Committee on Curriculum Studies K-12. (1971). NSTA position statement on science education for the 70s. Science Teacher, 38(8) 46-47.

National Science Teachers Association. (1982). Science-technology-society: Science education for the 1980s (NSTA position statement). Washington, DC: Author.

Norris, S. P. (1985). The philosophical basis of observation in science and science education. Journal of Research in Science Teaching, 22(9), 817-833.

Novick, S., & Nussbaum, J. (1981). Pupils' understanding of the particulate nature of matter: A cross age study. Science Education, 65, 187-196.

Nussbaum, J. (1979). Children's conceptions of earth as a cosmic body: A cross age study. Science Education, 63, 83-93.

Nussbaum, J., & Novak, J. (1976). An assessment of children's concepts of the earth using structured interviews. Science Education, 60, 535-550.

Nussbaum, J., & Novick, S. (1982a). Alternative frameworks, conceptual conflict and accommodation: Toward a principled teaching strategy. Instructional Science, 11, 183-200.

Nussbaum, J., & Novick, S. (1982b). A study of conceptual change in the classroom. Paper presented at the annual meeting of the National Association for Research in Science Teaching, Lake Geneva, IL.

Nussbaum, J., & Sharoni-Dagan, N. (1983). Changes in second grade children's preconception about the Earth as a cosmic body resulting from a short series of audio-tutorial lessons. Science Education, 67, 99-114.

Osborne, R., & Freyberg, P. (1985). Learning in science: The implications of children's science. Portsmouth, NH: Heinemann.

Osborne, R. J., & Wittrock, M. C. (1983). Learning science: A generative process. Science Education, 67, 489-508.

Peterson, R., Bowyer, J., Butts, D., Bybee, R. (1984). Science and society: A source book for elementary and junior high school teachers. Columbus, OH: Merrill.

Piaget, J. (1969). The child's conception of the world. Totowa, NJ: Littlefield, Adams. (Original work published 1929).

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. Science Education, 66, 211-227.

Prawat, R. S. (1988). Promoting access: The role of organization and awareness factors (Elementary Subjects Center Series No. 1). East Lansing: Michigan State University, Center for the Learning and Teaching of Elementary Subjects.

Raizen, S., Baron, J. B., Champagne, A. B., Haertel, E., Mullis, I. V., & Oaks, J. (1989). Assessment in elementary school science education. Washington DC: National Center for Improving Science Education.

Ramsden, P. (1988). Studying learning: Improving teaching. In Improving learning. London: Kogan Page.

Renner, J. W., Stafford, D. G., Coffia, W. J., Kellogg, D. H., & Weber, M. C. (1973). An evaluation of the Science Curriculum Improvement Study. School Science and Mathematics, 73, 291-318.

Renner, J. W., Stafford, D. G., & Ragan, W. B. (1973). Teaching science in the elementary school. New York: Harper & Row.

Resnick, L. B. (1987). Education and learning to think. Washington, DC: National Academy Press.

Resnick, L. (1983). Toward a cognitive theory of instruction. In S. Paris, G. Olson, & H. Stevenson (Eds.), Learning and motivation in the classroom (pp. 5-38). Hillsdale, NJ: Erlbaum.

Resnick, L. B. (1983). Mathematics and science learning: A new conception. Science, 220, 477-478.

Roth, K. J. (1984). Using classroom observations to improve science teaching and curriculum materials. In. C. W. Anderson (Ed.), Observing science classrooms: Perspectives from research and practice (1984 yearbook of the Association for the Education of Teachers in Science, pp. 77-102). Columbus, OH: ERIC Center for Science, Mathematics, and Environmental Education.

Roth, K. J. (1985a). Conceptual change learning and student processing of science texts. Unpublished doctoral dissertation, Michigan State University, East Lansing.

Roth, K. J. (1985b). Food for plants teacher's guide (Research Series No. 153). East Lansing, MI: Institute for Research on Teaching, Michigan State University.

Roth, K. J. (1986). Conceptual-change learning and student processing of science texts (Research Series 167). East Lansing, MI: Institute for Research on Teaching, Michigan State University.

Roth, K. J. (1987, April). Helping science teachers change: The critical role of teachers' knowledge about science and science learning. Paper presented at the annual meeting of the American Educational Research Association, Washington, DC.

Roth, K. J. (in press-a). Developing meaningful conceptual understandings in science. In B. F. Jones & L. Idol (Eds.), Dimensions of thinking and cognitive instruction. Hillsdale, NJ: Erlbaum.

Roth, K. J. (in press-b). Learning to be comfortable in the neighborhood of science: An analysis of three approaches to elementary science teaching. In W. Saul (Ed.), Vital connections: Children, science and books.

Roth, K. J. (1989, March). Subject matter knowledge for teaching science: Or How long does it take oxygen to get to the cells? Paper presented at the annual meeting of the American Educational Research Association, San Francisco.

Roth, K. J., & Anderson, C. W. (1987). The power plant: Teacher's guide to photosynthesis (Occasional Paper No. 112). East Lansing: Michigan State University, Institute for Research on Teaching.

Roth, K. J., Anderson, C. W., & Smith, E. L. (1987). Curriculum materials, teacher talk, and student learning: Case studies in fifth-grade science teaching. Journal of Curriculum Studies, 19, 527-548.

Roth, K. J., Smith, E. L., and Anderson, C. W. (1983, April). *Students' conceptions of photosynthesis and food for plants*. Paper presented at the annual meeting of the American Educational Research Association, Montreal, Canada.

Rowe, M. B. (1968). SCIS in the inner city school. *Science Curriculum Improvement Study Newsletter*, *11*, 6-7.

Rowe, M. B. (1978). *Teaching science as continuous inquiry. A basic*. New York: McGraw-Hill.

Rumelhart, D. E., & Norman, D. A. (1981). Analogical processes in learning. In J. R. Anderson (Ed.), *Cognitive skills and their acquisition* (pp. 335-339). Hillsdale, NJ: Erlbaum.

Rutherford, F. J. (1986, November). *Children and science*. Keynote address presented at the Children, Science, and Books Conference sponsored by the Library of Congress, Washington, DC.

Rutherford, F. J., & Ahlgren, A. (1988). Rethinking the science curriculum. In R. S. Brandt (Ed.), *Content of the Curriculum: 1988 Yearbook of the Association for Supervision and Curriculum Development* (pp. 75-90). Washington, DC: Library of Congress.

Rutherford, F. J., Ahlgren, A., Warren, P., & Merz, J. (1987). Project 2061: Education for a changing future. In A. B. Champagne and L. E. Hornig (Eds.), *The science curriculum: The report of the 1986 National Forum for School Science*. Washington, DC: American Association for the Advancement of Science.

Science Curriculum Improvement Study. (1970). *SCIS Composite teacher's guide*. Chicago: Rand McNally.

Shann, M. H. (1977). Evaluation of an interdisciplinary, problem solving curriculum in elementary science and mathematics. *Science Education*, 61, 491-502.

Shuell, T. J. (1986). Cognitive conceptions of learning. *Review of Educational Research*, *56*, 411-436.

Shymansky, J., Kyle, W., & Alport, J. (1983). The effects of new science curricula on student performance. *Journal of Research in Science Teaching*, *20*(5), 387-404.

Simpson, R., & Anderson, N. (1981). *Science, students, and schools*. New York: Wiley.

Sirotnik, K. A. (1983). What you see is what you get--consistency, persistency, and mediocrity in classrooms. *Harvard Educational Review*, *53*, 16-31.

Slinger, L. A., Anderson, C. W., & Smith, E. L. (1983). *Studying light in the fifth grade: A case study of text-based science teaching* (Research Series No. 129). East Lansing: Michigan State University, Institute for Research on Teaching.

Smith, D.C., & Neale, D.C. (1987, April). The construction of expertise in primary science: Beginnings. Paper presented at the annual meeting of the American Educational Research Association, Washington, DC.

Smith, E. L. (1983). Teaching for conceptual change: Some ways of going wrong. In H. Helm & J. Novak (Eds.), Proceedings of the international seminar of misconceptions in science and mathematics (pp. 57-66). Ithaca, NY: Cornell University.

Smith, E. L., & Anderson, C. W. (1984). Plants as producers: A case study of elementary science teaching. Journal of Research in Science Teaching, 21, 685-698.

Smith, E. L., & Anderson, C. W. (1987, April). The effects of training and use of specially designed curriculum materials on conceptual change teaching and learning. Paper presented at the annual meeting of the National Association for Research in Science Teaching, Washington, DC.

Smith, E. L., & Sendelbach, N. B. (1982). The program, the plans, and the activities of the classroom: The demands of activity-based science. In J. Olson (Ed.), Innovation in the science (pp. 72-106). New York: Nichols.

Stake, R. E., & Easley, J. (Eds.). (1978). Case studies in science education (Vols. 1 & 2). Urbana: University of Illinois, Center for Instructional Research and Curriculum Evaluation and Committee on Culture and Cognition.

Stead, B. F., & Osborne, R. J. (1980). Exploring students' concepts of light. Australian Science Teachers Journal, 26(3), 84-90.

Tasker, R. (1981). Children's views and classroom experiences. Australian Science Teachers Journal, 27(3), 33-37.

Tinker, R. F. (1987). Network science arrives: National Geographic-coordinated school experiment generates student-scientists. Hands on!, 10(1), 10-11. Cambridge, MA: Technical Education Research Centers.

Tobin, K. (1988). Learning in science classrooms. Paper presented at the Biological Sciences Curriculum Study 30th anniversary symposium on curriculum development for the year 2000, Colorado Springs, CO.

Trojcak, D. A. (1979). Science with children. New York: McGraw-Hill.

Tweney, R. D., & Walker, B. J. (in press). Science education and the cognitive psychology of science. In B. F. Jones & L. Idol (Eds.), Dimensions of thinking and cognitive instruction. Hillsdale, NJ: Erlbaum.

Trowbridge, D., & McDermott, L. (1980). Investigation of student understanding of the concept of velocity in one direction. American Journal of Physics, 48, 1020.

Weiss, I. (1978). Report of the 1977 national survey of science, mathematics, and social studies Education. Research Triangle Park, NC: Research Triangle Institute, Center for Educational Research and Evaluation.

Weiss, I. R. (1987). *Report of the 1985-86 national survey of science and mathematics education*. Washington, DC: National Science Foundation.

West, L. H. T., & Pines, A. L. (1985). *Cognitive structure and conceptual change*. Orlando, FL: Academic Press.

White, B. Y. (1984). Designing computer games to help physics students understand Newton's laws of motion. *Cognition and Instruction*, 1(1), 69-108.

Wolfinger, D. M. (1984). *Teaching science in the elementary school: Content, process, and attitude*. Boston: Little, Brown.

Yager, R. E. (1980). *Analysis of current accomplishments and needs in science education*. Columbus, OH: ERIC/SMEAC Clearinghouse for Science, Mathematics, and Environmental Education.

Yager, R. E., & Hofstein, A. (1986). Features of a quality curriculum for school science. *Journal of Curriculum Studies*, *18*, 133-146.