DOCUMENT RESUME

ED 320 755 SE 050 587

AUTHOR	Narode, Ronald; And Others
TITLE	Teaching Thinking Skills: Science.
INSTITUTION	National Education Association, Washington, D.C.
REPORT NO	ISBN-0-8106-0202-4
PUB DATE	87
NOTE	50p.; Produced in cooperation with the NEA Mastery in Learning Project.
AVAILABLE FROM	NEA Professional Library, P.O. Box 506, West Haven, CT 06516.
PUB TYPE	Reports - Descriptive (141) -- Guides - Non-Classroom Use (055)
EDRS PRICE	MF01 Plus Postage. PC Not Available from EDRS.
DESCRIPTORS	Cognitive Development; Concept Formation; *Critical Thinking; Elementary School Science; *Elementary Secondary Education; Experiential Learning; Inquiry; *Learning Theories; *Problem Solving; Process Education; Science Activities; Science Curriculum; Science Education; *Science Instruction; *Secondary School Science; Teaching Methods
IDENTIFIERS	*Socratic Method

ABSTRACT

This document addresses some of the factors involved in teaching critical thinking skills in the science classroom. It contains sections that deal with: (1) pair problem solving--creating a Socratic learning environment (emphasizes the role of the teacher); (2) writing to learn science (the thought-process protocol); (3) integrating science process skills into the regular curriculum; (4) thinking skills in content area instruction; (5) activity-based elementary science instruction; (6) improving students visual-spatial abilities; (7) using heuristics (including concept mapping and the Vee diagram); (8) the role of student misconceptions in teaching critical thinking; (9) multiple representations as an important instrucational tool; (10) the laboratory as a place where students can make discoveries; (11) the learning cycle of the Science Curriculum Improvement Study (SCIS) which includes exploration, innovation, and discovery; and (12) classroom management issues. A bibliography is also included. (TW)

Teaching Thinking Skills: Science

Ronald Narode
Marcia Heiman
Jack Lochhead
Joshua Slomianko

nea

A National Education Association Publication

Teaching Thinking Skills:
Science

Ronald Narode
Marcia Heiman
Jack Lochhead
Joshua Slomianko

Produced in cooperation with
the NEA Mastery In Learning Project

nea PROFESSIONAL LIBRARY
National Education Association
Washington, D.C.

Note

The opinions expressed in this publication should not be construed as representing the policy or position of the National Education Association. Materials published as part of the Building Students' Thinking Skills series are intended to be discussion documents for teachers who are concerned with specialized interests of the profession.

Library of Congress Cataloging-in-Publication Data

Teaching thinking skills.

(Building students' thinking skills)
Bibliography: p.
1. Science—Study and teaching. I. Narode, Ronald.
II. National Education Association of the United States
Q181.T354 1987 507 87-5611
ISBN 0-8106-0202-4

CONTENTS

The Authors

Ronald Narode is a Lecturer, Cognitive Processes Research Group, University of Massachusetts, Amherst.

Marcia Heiman is Director, Learning to Learn Program, Boston College, Chestnut Hill, Massachusetts.

Jack Lochhead is Director, Cognitive Processes Research Group, University of Massachusetts, Amherst.

Joshua Slomianko is President, Learning Associates, Inc., Cambridge, Massachusetts.

The Advisory Panel

Debra Lynn Bickford, teacher and Science Chairperson, Hillside Junior High School, Simi Valley, California

Doris Cruze, teacher, Flood Middle School, Englewood, Colorado

Carol Ann Harlos, Science Magnet School, Zoo Component, Buffalo, New York

Wil S. Higuchi, Biology and Science 8 Instructor, Sidney Public Schools, Nebraska

Francene Kaplan, Instructor, Secondary Education, Adult School, Huntington Beach, California

Donald C. Orlich, Professor, Department of Educational Administration and Supervision, Washington State University, Pullman

INTRODUCTION

The football team of Small City, Iowa, has two new coaches. In preparation for an important weekend match with the neighboring town, Big Falls, team members spent the entire week sitting in the stands watching their coaches reenact dramatic moments from the history of football. At the game, Small City lost by a score of 38-0.

We know that practice in any area means that players play and coaches coach. Anyone would be able to tell the coaches from Small City that they are setting up their players for failure by putting the team in a passive learning situation while they—the coaches—actively demonstrate the skills to be acquired. Yet few apply the conclusion from this analogy to formal education—and fewer still to the teaching of science.

Science is a field in which trial-and-error, experimentation, and hypothesis testing are fundamental; yet we teach students how to memorize a set of, say, 10 neat steps that *summarize* the scientific process, without letting them *experience* this process. In teaching science, we should keep in mind the sports analogy: critical thinking in science involves a set of skills, and like skills in other areas, it is best developed through frequent practice and good coaching.

Developing critical thinking skills in science requires *active* learning (10).* And, for process-oriented science instruction, this activity ought to be problem solving. It is unlikely that students will acquire good thinking skills by listening to a lecture—even one that is well-prepared and well-delivered. The necessary shift from teacher-centered classrooms to student-centered classrooms is a revolutionary one—one that requires teachers to look at classroom organization and the curriculum itself in a new way. In this monograph we will suggest some ways to help you bring active, critical thinking activities into the science classroom.

*Numbers in parentheses appearing in the text refer to the Bibliography beginning on page 46.

PAIR PROBLEM SOLVING: CREATING A SOCRATIC LEARNING ENVIRONMENT

Asking students to express their thoughts aloud while they engage in problem solving externalizes the thinking process, and gives the speaker—as well as the listener—feedback on what is understood and what is still only vaguely processed. Further, expressing one's ideas is a catalyst for the creation of new ideas, and it also forces the speaker to listen to what is said in a way that cannot occur when s/he is working quietly and alone. This self-monitoring of one's thought processes is a higher-order thinking skill; psychologists sometimes refer to this skill as *metacognition*.

Pair problem solving is most successful as an instructional aid when it is conducted in an environment that simulates the clinical interview. That is, when students work in pairs—one student acting as problem solver, the other as listener—they learn to "interview" each other while solving problems. Some of the advantages to pair problem solving are that it:

- Helps students work through problems systematically, rather than jumping ahead and making guesses that have not been thought through
- Helps students find out which parts of a problem they understand—and where they get stuck
- Makes the problems more engaging
- Encourages the development of metacognitive skills (reflecting on initial and subsequent thoughts, evaluating methods and heuristics, self-checking)
- Teaches communication skills
- Exposes students and teachers to several points of view and to various solution approaches
- Encourages the formation of study groups
- Establishes a support group (allowing science-week students to see that they are not alone and that others also have difficulties)
- Fosters cooperation (as a social value as well as a classroom aid).

Pair problem solving requires carefully prescribed roles for the problem solver and the listener. The problem solver must read the problem aloud and verbalize as best he/she can all of his/her thoughts while working toward a solution. The listener must encourage the solver to explain all his/her ideas so that the listener understands not only each step in the solver's solution but also the reasons for each step. Whimbey and Lochhead have described the listener's role in *Problem Solving and Comprehension*:

- The listener must actively follow along with the problem solver, sometimes asking the solver to wait a bit until the listener has actively followed each step. If the solver gets ahead of the listener, the listener will not be able to check the solver's solution *process*.
- The solver can use such wait-time to again check to see if any steps were left out or done in error.
- The listener and problem solver should work *together* on the problem—the listener should not be sitting back, waiting for the solve to finish, but should follow along while the solver is working through the problem.
- When the listener sees an error, s/he should point it out—*not* provide the correct answer.
- The listener should require that the solver continually talk aloud the process—what is not externalized cannot be monitored.
- The listener may suggest strategies for externalizing the thinking process—such as asking the solver to draw a diagram for a complex problem. (47)

Pair problem solving can be highly effective. Hunter and others, using *Problem Solving and Comprehension* (47) in a pair-problem-solving format, reported significant immediate and long-term student gains (17). Students in their six-week pre-college program gained an average of 115 points on the Preliminary Scholastic Aptitude Test (PSAT). Moreover, a longitudinal study showed that students who participated in this program were twice as likely to complete college degree requirements in science programs as were similar students who entered the same college without taking this program.

As with all instructional methods, pair problem solving requires teacher supervision. Teachers in a pair-problem-solving class should move from pair to pair, helping students to stay on track with the problem and with their separate roles. For example, it may happen that one of the two students will overwhelm the other, resulting in one confident student and one confused student. At other times, students may work separately and compare answers; this short-circuits the metacognition involved in describing the solution process. Teachers should rotate student pairs throughout the term; working with a variety of partners allows for more diversity of thought and a more cohesive classroom. Finally, to ensure that the listeners are in fact listening, they should occasionally be asked to summarize the steps of the solver's solution to a third person; this person can be either the teacher or a student observer of the pair's dialogue.

THE ROLE OF THE TEACHER: AUTHORITY OR COACH?

In order to teach with pair problem solving, teachers should be both good problem solvers and skilled interviewers. Above all, teachers should be patient and understanding listeners. For critical thinking to occur, students must feel free to make errors publicly. They must understand that expert problem solvers seldom think flawlessly. Experts suffer memory lapses, they misread passages, their thinking sometimes proceeds down blind alleys, they make arithmetic errors, they get stumped—but they also know that they sometimes suffer these human frailties, so they attend to them.

The essence of good problem solving is self-correction. However, most students view science as an endeavor in which teachers provide the correction. To overcome that preconception, teachers should avoid the temptation to supply a more elegant solution or to insist that certain strategies be employed in the solution of a problem. In short, teachers should become facilitators of learning, not sole dispensers of truth.

Teachers should occasionally model the role of problem solver, verbalizing all the thinking on a problem including the dead ends, the flaws, and the inelegancies that accompany most problem solving. It is useful to deliberately make mistakes for students to discover. These detailed thought-process solutions are far preferable to simply giving the answer to a problem. Teachers must relinquish the safe seat of authority and step into the classroom, walking among students, listening to their solutions, and asking questions that encourage them to discover their own solutions.

WRITING TO LEARN SCIENCE: THE THOUGHT-PROCESS PROTOCOL

Middle school and high school science students can further clarify their thinking processes by "thinking aloud on paper." The metacognitive skills of reflection, careful reading, paraphrasing to oneself, and self-conscious evaluation of thinking-in-progress can be developed in private on paper, as well as in public in pair problem solving. Students can be asked to write several *thought-process protocols* on challenging problems from different topics they are studying. In doing so, students should record on paper every thought, every step toward a solution. Initially, teachers should evaluate the protocols solely on the basis of how well students record their thoughts. They should not be concerned with students' grammar, sentence constuction, or organization. Until the third or fourth protocol, teachers should not even grade students on the correctness of their solutions. Instead, they should make written comments on the protocols—addressing the *process*, not whether students arrive at the right answer. For example. a teacher might write, "This problem might be clearer if you drew a diagram of it," or "What happened to the unit of heat in this problem? Can you find the step you skipped?"

Students can write protocols in class, as homework, and whenever they get "stuck" on difficult problems; that is, teachers should encourage students to write down their thoughts whenever they feel frustrated by a problem—even on an exam.

As mentioned previously, critical thinking is complex thinking, and as such, it is often slower than "noncritical thinking." The thought-process protocol slows students down so that they do not jump to conclusions too hastily, as many poor problem solvers so often do. Furthermore, the act of writing provides weak students with a starting point. The solution begins with the first sentence—even if that sentence is a statement of confusion. By declaring confusion and then setting to the task of describing it, students often clear up their own misconceptions. If they don't, they have at least posed a question for the teacher to answer. The teacher is a greater resource to the student when responding to the comment, "I can do this problem up to here, but then I get stuck," rather than "I can't do this problem."

Writing thought-process protocols results in the following benefits for student learning:

- Students begin to distinguish between what they know and what they need to learn.
- Students start to recognize the steps in problem solving that they often skip over.
- Students begin to value the importance of working through problems systematically.

Once students have produced such protocols, they should be asked to read their own work—or to exchange papers and critique the work of others. Protocols can be the focus of classroom discussion, with students debating the merits of the different approaches they have taken in solving a problem. Writing protocols enables students to talk about problems in science; it helps them make the transition from the language of *symbols* to the language of *words*. Thus, students can talk about problems—and their solutions—with greater understanding, rather than in a rote-memory fashion.

Writing allows students to translate symbolic, mathematical information into the language of daily speech and thought. It helps students to be less "mechanical" in their problem solving and alerts them to logical errors and gaps in procedure and analysis. Horton, Fronk, and Walton (16) found that asking students to turn in written summaries of their chemistry lecture notes brought to the surface students' errors and misconceptions in problem solving, and resulted in significantly higher test performance for summary writers than for a control group of nonwriters.

INTEGRATING SCIENCE PROCESS SKILLS INTO THE REGULAR CURRICULUM

In recent years, many science textbook publishers have included instruction in basic science processes in their materials. Students do more than memorize facts with these new science materials: they learn to observe, classify, measure, and use time and space relationships; in some cases, these new materials also help students infer and predict. Once students have acquired these basic skills, they are able to progress to more sophisticated skills—controlling variables, interpreting data, formulating hypotheses, defining operationally, and experimenting. However, there is little published material available that integrates these more complex skills into science teaching.

Padilla, Okey, and Garrard (34) addressed this issue in a study in which sixth- and eighth-grade middle school teachers systematically integrated complex process skill instruction into their science curriculums. The steps they used, adapted from earlier work by Padilla (33) and Tobin and Capie (44), are illustrated here in a unit on the senses:

1. The teacher poses a question which can be investigated—e.g., "Are some body parts more receptive to touch than others?"
2. Students with the help of the teacher form several appropriate hypotheses: "Fingertips are more sensitive to touch than are the palms of the hand or the forearm."
3. Students identify variables, perhaps using brainstorming techniques.
4. The manipulated and responding variables are selected and operationally defined. Still other variables need to be controlled. For example, students may decide that the ability to perceive the touch of a pencil lead is a good operational definition for the responding variable. Variables such as the instrument and force used to touch the body parts need to be controlled.
5. Students *design the experiment* and set up an appropriate table. That is, the number of trials for each body part and the order and conditions under which testing occurs must be specified. An appropriate data table should be discussed and designed by the students.
6. Groups of students *conduct the experiment*. While this is an important part of the activity, it does not overshadow the planning or data analysis portions.

7. Students *organize data* onto a class chart and make generalizations. These generalizations may take the form of conclusions or of new hypotheses. (Emphasis added; 34, p. 279)*

The researchers found that it was most effective to introduce the new skills during a two-week introductory unit that stressed designing and carrying out experiments; this instruction was followed by one period-long process skill activity each week, integrated into each content-area unit of the curriculum. Students who received ongoing process skill instruction were better able to construct hypotheses and identify variables than were students who received introductory process skill instruction with no followup. A list of the process skill lessons used in this experiment is shown in Figure 1.

This experiment has two important implications for teaching science to middle-school-aged students: (1) it appears that science process skills can be successfully taught to middle school students, and further that this skill instruction can be readily integrated into content-area instruction, and (2) ongoing reinforcement through process skill activities in different content areas is apparently more effective than short-term instruction in process skills alone.

*"The Effects of Instruction on Integrated Science Process Skill Achievement," by Michael J. Padilla, James R. Okey, and Kathryn Garrard, *Journal of Research in Science Teaching* Copyright © 1984 John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.

Unit Topic	Length of Unit (Wks)	Lesson Topic
Grade 6		
The Senses—sight	1	Sight—depth perception
The Senses—hearing	1½	Hearing—boys vs. girls
The Senses—touch	1½	Touch—sensitivity to touch
The Senses—smell or taste	1	Smell—olfactory fatigue
Properties of Matter	2	Data tables and graphing
		Effect of the number of coils on an electromagnet
Sound	2	Lengths, vibrations, and pitch
Light	2	Effect of object distance or image distance
Heat	2	Water and melting time
		Melting ice
		Evaporation and surface area
Grade 8		
Universe and Space	3	Heat from the sun
		Graphing and interpreting data
Weather and Atmosphere	2½	Evaporation of water
		Variations in temperature at different heights
		Observing and recording air temperatures
Earth Matter	2	Effect of a dissolved substance on the boiling point
		Effect of heating on the temperature of an ice-cube-water mixture
Rocks and Minerals	3½	Measuring the density of rock samples
		Weathering of rocks
Earth History	2	Radioactive half-life studies

Figure 1. Integrated science process skills.

SOURCE "The Effects of Instruction on Integrated Science Process Skill Achievement," by Michael J Padilla, James R Okey, and Kathryn Garrard, *Journal of Research in Science Teaching*, 2̇ no 3, 1984, p 281

MEASURING THE EFFECTS OF TEACHING THINKING IN A SCIENCE CLASSROOM

Padilla, Okey, and Garrard (34) measured the effects of their experiment by assessing students' performance on the Test of Integrated Process Skills (TIPS) and the Test of Logical Thinking (TOLT). Both tests have been shown to be reliable and valid instruments for measuring the intended abilities (9, 44). TIPS and TOLT are useful in measuring the kinds of reasoning abilities needed in science, and can be used with students in middle school through high school.

TIPS contains items that test students' abilities to hypothesize, identify variables, construct operational definitions, design experiments, and interpret data. Two items from TIPS are shown in Figure 2.

Hypothesizing TIPS Item

John cuts grass for seven different neighbors. Each week he makes the rounds with his lawn mower. The grass is usually different in the lawns—in some it is tall but not in others. He begins to make hypotheses about the height of grass. Which of the following is a suitable hypothesis he could test?

1. Lawn mowing is more difficult when the weather is warm.
2. The amount of fertilizer a lawn receives is important.
3. Lawns that receive more water have longer grass.
4. The more hills there are in a lawn the harder it is to cut.

Operationally Defining TIPS Item

Students in a science class did an experiment. In it they pointed a flashlight at a screen. They put the flashlight at different distances from the screen. They then measured the size of the lighted spot.

Which of the following would be an appropriate measure of the size of the lighted spot?

1. The diameter of the flashlight
2. The size of the batteries in the flashlight
3. The size of the screen
4. The radium of the spot on the screen.

Figure 2. Two sample items from the Test of Integrated Process Skills.

SOURCE: "The Effects of Instruction on Integrated Science Process Skill Achievement," by Michael J. Padilla, James R. Okey, and Kathryn Garrard, *Journal of Research in Science Teaching*, 21, no. 3, 1984, p. 282

TOLT uses two types of items to test students' logical thinking in science. In one format, students must choose not only a correct answer to a problem posed, but also a correct reason for the answer. This minimizes the effect of guessing. In the second format, students are asked to list possible combinations of several variables. Examples of questions in each of these formats are shown in Figure 3.

Proportional Reasoning TOLT Item

Four large oranges are squeezed to make six glasses of juice. How much juice can be made from six orange ?

a. 7 glasses
b. 8 glasses
c. 9 glasses
d. 10 glasses
e. Other

Reason:

1. The number of glasses compared to the number of oranges will always be in the ratio 3 to 2.
2. With more oranges, the difference will be less.
3. The difference in the numbers will always be 2
4. With four oranges the difference was 2. With six oranges the difference would be 2 more.
5. There is no way of predicting.

Combinational Reasoning TOLT Item

In a new shopping center, four store locations are going to be opened on the ground level.

A BARBER SHOP (B), a DISCOUNT STORE (D), a GROCERY STORE (G), and a COFFEE SHOP (C) want to move in there. Each one of the stores can choose any one of four locations One way that the stores could occupy the four locations is BDGC. List all other possible ways that the stores can occupy the four locations.

More spaces are provided on the Answer Sheet than you will need.

Figure 3. Two sample items from the Test of Logical Thinking.

SOURCE: "The Effects of Instruction on Integrated Science Process Skill Achievement," by Michael J Padilla, James R Okey, and Kathryn Garrard, *Journal of Research in Science Teaching*, 21, no. 3, 1984, p 282

We consider the development of tests such as TIPS and TOLT* to be of great importance to the thinking-in-the-science-classroom movement. At present, there is little else available that measures higher-level thinking in science. A recent study of 12 standardized science tests showed that 90 percent of the items from all tests required only recall, and 7 of the tests required only recall abilities on *all* test items (30).

*Both TIPS and TOLT are available from Michael J Padilla, Department of Science Education, University of Georgia, Athens, GA 30602

THINKING SKILLS IN CONTENT-AREA INSTRUCTION

The Learning to Learn (LTL) Thinking Improvement System (12, 13) represents another approach to integrating thinking skills into the science curriculum. Developed over a 20-year period, the LTL system is based on research on the critical thinking skills of successful learners. This system, which has applications for content areas across the curriculum, has particular relevance to science teaching. Learning to Learn teaches students to actively question the material they are learning, to break up complex ideas and tasks into manageable components, to obtain ongoing feedback on their learning progress, and to direct their learning toward their teachers' instructional objectives.

A key to the LTL system is teaching students to generate questions from course material. For example, Figure 4 illustrates a beginning chemistry student's attempt to ask a question using notes she took in class. As any chemistry teacher can see, the level of this question is too low: it asks a "What is it?" question when a "How do you do it?" question is in order. A better question, written later on subsequent material by the same student, follows in Figure 5.

Another example of students' improved question-asking abilities is shown below. During the first week of LTL instruction, students studying oceanography asked low-level, "What is it?" questions. Later, students asked complex questions that are addressed by the teacher—and by the field. For example, here are some questions handed in by failing students during the first week of using Learning to Learn methods; the questions are supposed to reflect information presented in an oceanography course. Since oceanography is a branch of applied physics, good questions would probably be problem-solving ones. Certainly, good questions would be more complex than the ones these students submitted.

Student-Generated Questions: First Week of LTL Instruction

Student A: What is a mid-ocean ridge?
What is a trench?
What is the speed of continental drift?

Student B: How is a beach formed?
What is a delta?
What is turbidity current?

What are some common values for Ksp?

	Ksp		Ksp
$AgBrO_3$	5×10^{-5}	Ag_2CrO_4	9×10^{-12}
Ag_2SO_4	7×10^{-5}	$AgBr$	5×10^{-13}
$AgOH$	1.5×10^{-8}	AgI	1×10^{-16}
$AgIO_5$	2×10^{-8}	Ag_2S	1.6×10^{-49}
$AgCl$	1×10^{-10}		

Figure 4.

What are the 2 methods for balancing oxid-Reduct. equat.? Give Procedure

Another Ox. Red Equation (Balance)

$$\underset{+2\ -2}{CuS_{(s)}} + HNO_3\left(\substack{dilute\\aq}\right) \rightarrow \underset{+2}{Cu^{++}} + \underset{0}{S} + \underset{+5}{NO_3^-} + \underset{+2}{NO}$$

A. Ion - Electron Method

$$[\ CuS \rightarrow Cu^{++} + S + 2e^-\ ]\times 3 \quad ox$$

$$[\ 3e^- + 4H^+ + NO_3^{(-2)} \rightarrow NO + 2H_2O\ ]\times 2 \quad Red$$

$$3CuS \rightarrow 3Cu^{++} + 3S + 6e^-$$

$$6e^- + 8H^+ + 2NO_3^- \rightarrow 2NO + 4H_2O$$

B. ox. st. change method

	o-s-ch	$\times$ o.s.ch
$3[S(-2) \rightarrow S(0)]$	$+2$	$+6$
$2[N(+5) \rightarrow N(+2)]$	-3	-6

$$2H^+ + 3CuS + 2HNO_3 \rightarrow 3S + 2NO + 3Cu^{++} + 4H_2O$$

Figure 5.

Student C. How are sand bars formed?
Name and describe the four types of dams.
What is isostatic balance?

Contrast those questions with the ones below, which the same students submitted four weeks after beginning to use LTL techniques:

Student-Generated Questions After Four Weeks of LTL Instruction

Student A: Contrast water hitting hard rock with waves rolling up on a beach of sand.

Contrast difference between waves which hit a beach straight on and those which hit at a particular angle.

Student B: How does the theory of "plates" relate to the age of the sea floor?

What geologic feature is formed at the crack where the material under the earth comes to the surface?

Student C: Give a short explanation of how we use knowledge of the earth's magnetic field reversal to explain sea floor drift.

As these questions show, the students have begun to look at their coursework in more integrated ways. Unlike the student's initial questions, these questions reflect the issues addressed by the field under study.

This kind of improvement comes about by having students continually asking questions, by providing all students with models of the better students' questions, by discussing in class the features of successful questions, and by having students work together in pairs so they can give each other feedback on their question-generating.

The LTL system has been validated for college students by the U.S. Department of Education's Joint Dissemination Review Panel, and it has recently been expanded for use in middle schools and high schools. Learning to Learn abandons the technique of teaching students summarized facts; rather, it helps them to approach their work using a scientific methodology that encourages them to continually create and test hypotheses about what they are learning.

Another aspect of LTL calls for students to integrate newly learned material into their existing knowledge and to draw conclusions and recognize analogous situations. The following examples will illustrate this set of strategies:

Students in a chemistry class learn that a calorie is a unit used to measure heat energy. Rather than just asking students to proceed through a set of laboratory manual exercises in heat measurement, Mrs. Grant asks her class to generate questions about the concept "calorie." Students work in pairs, writing questions about the concept. Several students submit a variation on the following question:

> "Is the kind of calorie used for measuring heat in burning wood or oil the same kind of calorie used when a person gains weight?"

Mrs. Grant asks the students to work in small groups, constructing possible experiments that could enable them to answer this question. Each suggested experimental design is discussed in class. The class agrees that the design most likely to answer the question is this:

> *Operational definition of a calorie:* The amount of heat energy needed to raise one gram of water one degree centigrade.
>
> *Test of hypothesis:*
>
> Look in a diet book to see how many calories are in a gram of vegetable oil.
>
> Using laboratory equipment, burn a gram of vegetable oil beneath a measured beaker of water. Using the gain in temperature of the water as a metric, calculate the number of calories in the gram of vegetable oil.
>
> Compare this number with the diet book statement.

When the students complete the experiment, they find that the number of calories in their experiment seems to be 1,000 times greater than the number listed in the diet book. Mrs. Grant tells them that they have found the correct amount: the diet book "calories" is actually a shorthand term for kilocalorie. The students have learned how to find a *measurable* connection between a commonly known concept and one found in scientific work.

Mr. Fine wants his eighth grade students to see how concepts can be interrelated in science. His students have been studying a chapter on respiration in plants and animals. To illustrate part of the book's discussion of oxygen, Mr. Fine sets up the following experiment: He lights a candle, then covers it with a glass. Without oxygen, the flame quickly dies. Later, he gives the students a thought experiment—one in which students are given an intellectual problem and asked to think through the results and their implications, rather than conducting the experiment itself. He asks them, working in pairs, to imagine the outcome of this experiment:

> Two mice are placed under glass; the first is placed under an empty glass, the second under a glass with a green plant What will the outcome be after 5 days?

Several pairs of students correctly hypothesize that the first mouse will die, while the second will remain alive. the CO_2 breathed out by the mouse will be absorbed by the plant each day, while the oxygen given out by the plant at night will keep the second mouse alive. The first m use will die because of lack of oxygen.

Soon after this discussion, Mr Fine introduces his students to what may be for them a scientific mystery. He uses the problem as a thought experiment. The problem is as follows:

> In the year 1694 the chemist Van Helmont designed an experiment to check a hypothesis about how green plants grow He hypothesized that green plants are made from water. Here is his experiment.
>
> "I dried 200 lb. of soil in an oven and put it in a container. I irrigated the soil with rainwater or distilled water. I planted a small plant of 5 lb. Nothing else was added. To prevent dust from collecting on the soil, I covered the container and left only a hole for the plant. After five years I took out the tree and weighed it. It weighed 169 pounds and 3 ounces. I did not weigh the leaves that fell in the four seasons. Then I took the soil and dried it. It weighed 200 pounds minus 2 ounces. Now the tree at the beginning of the experiment weighed 5 pounds. That means that the increase of more than 164 pounds was produced from water."*

Students are asked to discuss the experiment in pairs, generating questions and possible explanations for this phenomenon. The students are asked to consider the following questions during their hypothesizing: What was right in Van Helmont's experiment? What elements did he miss? Is there any relationship between this experiment and the oxygen experiment completed earlier?

Several student pairs construct a good working hypothesis based on the connection between the oxygen experiment and the Van Helmont experiment: that is, plants give and take elements from the air as well as from the soil.

When students are not simply presented with mechanical cookbook laboratory exercises, but rather are asked to generate their own questions and explanations from partially explained phenomena, they will become more active learners and will perform the hypothesizing and the searching for solutions that are the basis of scientific thought. Students may not always produce the "right" hypothesis—but in their search for questions and answers in science, they will learn about trial-and-error work and about the importance of data that validate their assumptions, and they will become more thoughtful and less "mechanical" when they work in the lab and learn from the text.

*Biological Sciences Curriculum Study © 1965. Reprinted with permission. Revised 3d edition © 1986 available from Kendall Hunt Publishing Company, Dubuque, Iowa.

ACTIVITY-BASED ELEMENTARY SCIENCE INSTRUCTION

A number of activity-based science curriculums have been made available to elementary school teachers in the past few years. Among these are the Science Curriculum Improvement Study (SCIS) and Science—A Process Approach. These curricula use direct experience, experimentation, and observation as the sources of students' learning about science. They are process-oriented: they emphasize *how* to obtain and understand information, not simply what the information is. Instead of textbooks, they have teacher's guides, sometimes supplemented with laboratory sheets or manuals.

As an example, the SCIS unit on Objects states the following among its learning objectives:

1. To describe an object by its properties: The child is given a soda cracker and asked to state as many properties of this object as possible. There is no time limit.
2. To group objects by material. A collection of objects, each made of a single material, is placed in front of the child. Materials are rubber, glass, plastic, metal, wood, paper, cloth. The child is asked to group them by material and to state why he has grouped in this way.
3. To order objects serially by a stated property: The child is presented with a random arrangement of blocks of wood of different lengths, thicknessess, and widths, to one side of which are glued sandpaper of different textures and colors. The child is asked to arrange the blocks in order in as many ways as possible and to state his reasons.
4. Simple Inference: The child is presented with a paper clip, a plastic button, a magnet, and an eraser, and is asked to play with them. A closed matchbox (containing a paper clip) is added to these four objects and the child is told that another one of these objects is inside the box. He is asked to name the hidden object and to give his reason. (1, p. 278)

In a third-grade SCIS physical science unit, students learn the concepts *subsystems*, *variables*, *planned experiments*, and *control of variables*. In one set of exercises, students are given four simple mechanical systems and are asked to name the variables affecting the following operations:

1. The time taken to transfer water with an eyedropper
2. The distance travelled by a toy truck
3. The distance stones are thrown by a slingshot
4. The level at which a syringe floats.

In a SCIS unit on temperature, upper elementary students devise and conduct experiments to find the melting temperature of ice and to see how solids, liquids, and gases expand and contract when they are warmed and cooled.

The activity-based approach to teaching is grounded in the commonly accepted notions that children learn by doing and that their learning proceeds from concrete through more formal, abstract stages. Boyd (6) and Rodriguez and Bethel (36) found that an inquiry/activity-based approach to science resulted in significant improvements in early elementary students' classification and oral communication skills. Students learned to observe and classify common objects through a process that helped them view and describe these objects in increasingly more abstract ways:

1. Each child is given a set of common objects (e.g., a marble, a paper clip, a rubber ball, a paper cut-out, a pipe cleaner) and asked to examine them and make observations about them.
2. The teacher moves around the classroom and stops by each child's desk, asking him or her what was noticed about the objects. The student might say, "This is red," or, "You can bend this." The teacher does *no prompting*; there is no instruction in ways of classifying or describing objects from teacher to students. However, the teacher might say, "What else do you see?"
3. The teacher then asks the students to put away the objects and draws them into a group for discussion of their individual observations. In most classes, there is a range of observations, from less to more abstract. For example, some students will describe an object functionally ("You play with this."), while others will describe it more formally ("This is round."). The teacher writes the descriptions on the board.
4. Students are then asked to work again with their materials, this time finding ways of grouping two or more objects in a category. As the teacher moves around the classroom, s/he asks each student to tell her/him why certain objects have been grouped together; a group is not accepted unless the child can supply an attribute that the items in the group share. Again, there is a range of answers from different children, and for different grouped objects (e.g., "These are all the same shape." "These are all small." "You can bend these." "These are made of paper.").

5. Another classroom discussion is held, and students supply their reasons for their categorizations.

As children move through these activities, they learn abstract ways of describing and classifying the objects they work with; their learning from each other in the classroom discussions is reinforced by further independent investigation. Not all objects need be described and classified visually; the teacher can bring in materials that promote description and categorization using touch, hearing, smell, and taste.

Boyd (6) and Rodriguez and Bethel (36) found that these activities had significant effects on a wide range of student abilities. Having tested the program mostly with students who began school with an educational disadvantage, they found that the program had marked, long-term effects on these students' academic success. Among first-grade nonreaders, the program produced significant changes in their early performance, as well as in their subsequent overall academic performance. In addition, the oral communication skills of the students in the inquiry program were strongly affected: they used a richer and more complex vocabulary and were more likely to speak in compound sentences than were students enrolled in a traditional elementary science program (with units such as "Frogs," "Fish," and "Energy"). Finally, inquiry program students were more able to work independently, and with greater concentration, than were nonprogram students.

In general, the research on activity-based elementary science programs shows that they produce numerous gains, both in students' skill acquisition and in their general intellectual functioning. Reviewing 57 controlled studies of such activity-based programs, Bredderman (7) found student gains on science process tests, in science content understanding, and in attitude toward science, as well as gains in creativity, intelligence, language, and mathematics.

This work has important implications for teachers of elementary science. First, it demonstrates that activity-based science instruction can achieve the general goals of elementary science education: to make students more aware of the world around them, and to develop intellectual skills that transfer to other areas of learning. Second, it reinforces the importance of letting students learn from *their own observations*, rather than requiring them to memorize facts supplied by the teacher.

IMPROVING STUDENTS' VISUAL-SPATIAL ABILITIES

Students' visual-spatial thinking abilities in all areas of science greatly affect their performance. The origin of this set of skills has been debated as part of the nature/nurture controversy: some believe that visual-spatial abilities are innate, while others believe that they are acquired through interactions with the environment.

In a recent study, Lord (29) demonstrated that these skills *can* be significantly improved through structured practice. Here are some examples of these practice exercises:

1. Give first graders pictures of several familiar animals. Ask students to work in pairs. Each pair of students looks at a picture; then one child closes his/her eyes and attempts to recall the animals in the picture. The listening child looks at the picture, checking the visualizing child's recall. On the next picture, the children exchange roles.
2. Give fifth graders a set of more complex representational pictures and/or a set of drawings of simple black or white geometric forms.

Visual-spatial practice exercises can be done with students at any academic level: they range from simple to complex and should be chosen to meet the needs and the skills of students of different ages and initial levels of ability.

USING HEURISTICS: CONCEPT MAPPING AND THE VEE DIAGRAM

A heuristic is an aid to solving a problem or understanding an idea. For example, outlining is a heuristic intended to help students see the relationships between major and subsidiary ideas or events. Novak and Gowin (31) have developed two heuristics that help students understand and explore complex relationships among sets of concepts; they call these *concept mapping* and the *Vee heuristic*. While both can be used across different content areas, they have particular relevance to the teaching of science in middle school through high school.

Concept maps show relationships between two or more ideas in the form of propositions. For example, "grass is green" is a valid proposition about the concepts *grass* and *green*. *Grass* as a concept may be further described and explored: it grows, it is a plant, etc. A concept map can graphically explore and illustrate these connections. The concept map in Figure 6, prepared from a science textbook by three seventh graders working together, shows some relationships among organic and inorganic matter found in oceans.

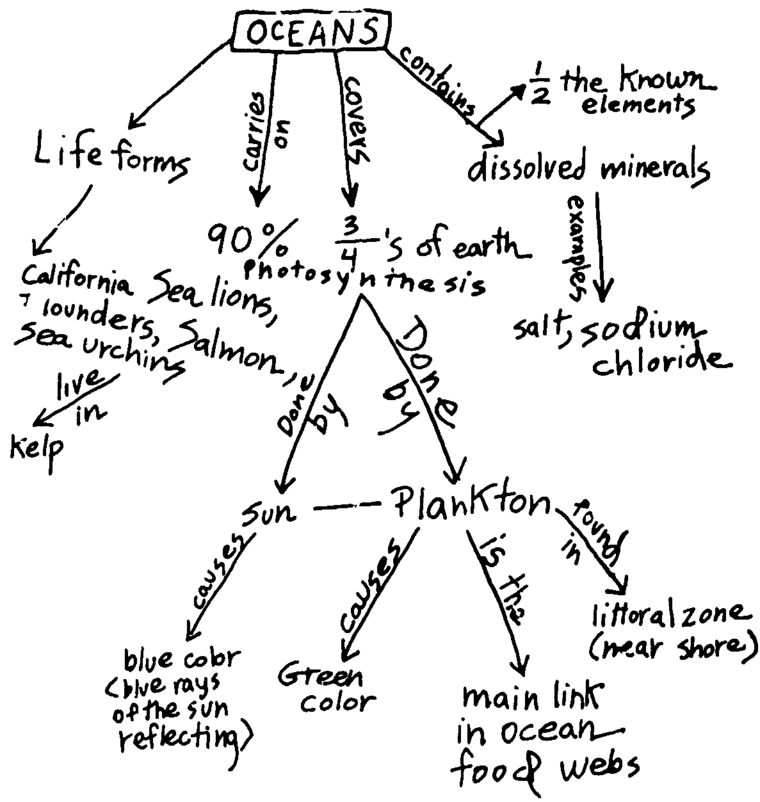


Figure 6. Concept map.

SOURCE: *Learning How to Learn*, by Joseph D Novak and D Bob Gowin, p. 22 Copyright © 1984 by Cambridge University Press. Reprinted with permission of Cambridge University Press

Like other thinking-improvement strategies we advocate in this monograph, concept maps help students understand ideas by externalizing them so that they can be readily examined. For example, Figure 7 externalizes—and thus makes clear—a student's misconceptions about the causes of the moon's changing phases. As the map shows, the student thinks that both the moon's rotation and the earth's shadows produce the different phases of the moon.

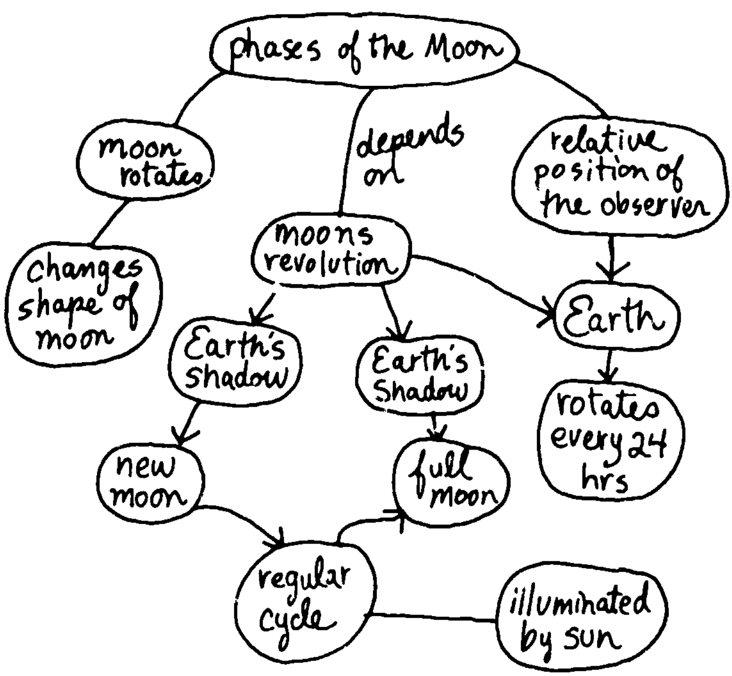


Figure 7. Concept map.

SOURCE: *Learning How to Learn*, by Joseph D Novak and D Bob Gowin, p 21 Copyright © 1984 by Cambridge University Press Reprinted with permission of Cambridge University Press

In teaching concept mapping, Novak and Gowin suggest that students be presented with a list of familiar words for objects (cat, house, tree) and another list of words for events (hurricane, running, holiday). During a discussion of the differences between these lists, the teacher then helps students come to see the first list as objects, the second as events. These are examples of concept words. The teacher later talks with students about linking words (with, is, causes, becomes). Finally, the teacher models some simple concept maps for students and, with students' suggestions, constructs others on the board for classroom discussion and analysis.

Novak and Gowin propose several criteria for evaluating concept maps. Such a map should illustrate a valid relationship between two concepts through the use of a line or an arrow; it should show hierarchy, with a more inclusive concept branching into subsidiary concepts; cross-links between different aspects of a concept should be drawn where relevant; and examples of the concept label should be included on the map. Of course, students' initial maps will be considerably less complex than this; these criteria should be seen as a set of working goals, not as the basis for marking a student's work "right" or "wrong." Missing parts of a concept map give the teacher information about those areas where the student needs clarification and guidance.

Novak and Gowin also suggest numerous ways to use concept mapping to aid student understanding. Particularly relevant to the science teacher are their suggestions for using this method to help students extract meaning from laboratory and field studies. They note that students often begin these studies without setting learning goals, that they simply begin recording data or manipulating apparatus in mechanical ways, without noting the meaning inherent in the proposed work. If students begin their work by constructing concept maps of important concepts and their interrelationships, they will be better able to interpret their observations and to fit them into a meaningful whole.

Novak and Gowin's second heuristic, the Vee diagram, was developed to address the problem of students' engaging in laboratory work in a cookbook manner, without connecting the ideas they were learning in science classrooms to the laboratory experiment at hand. Using Vee diagrams, students learn to understand the meaning and purpose of laboratory work, to relate the theory they learn in the classroom to their laboratory practice, and to use a focus question to orient their work. Figure 8 presents an example of a Vee diagram constructed by an "average" seventh grader doing lab work on cell study.

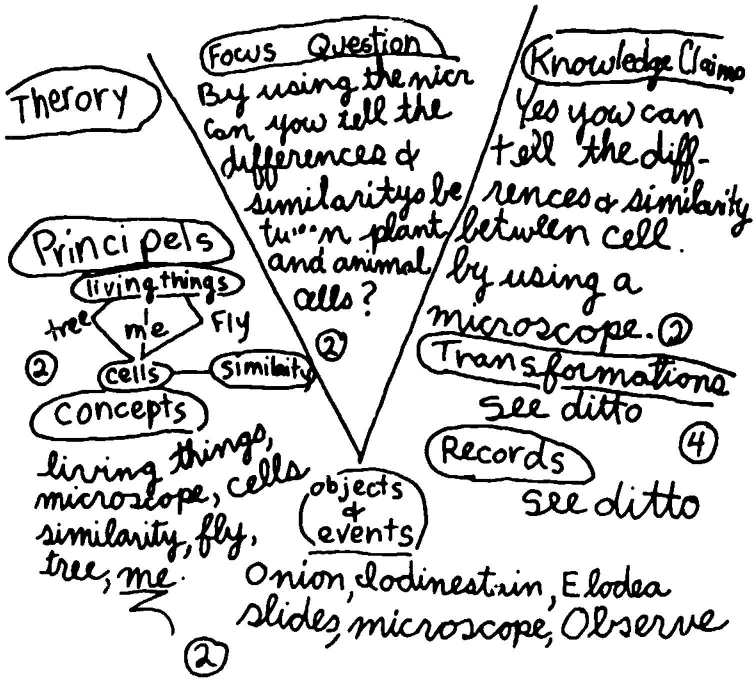


Figure 8. Vee diagram.

SOURCE *Learning How to Learn*, by Joseph D Novak and D Bob Gowin, p 58 Copyright © 1984 by Cambridge University Press Reprinted with permission of Cambridge University Press

A Vee that makes explicit the concepts, records, transformed records, and knowledge claims for heating ice water is shown in Figure 9. As the student works, s/he would add to a diagram such as this. For example, the student would start with the focus question, the events, and the concepts, and then begin recording data. The recorded data would be transformed and then knowledge claims extracted from it.

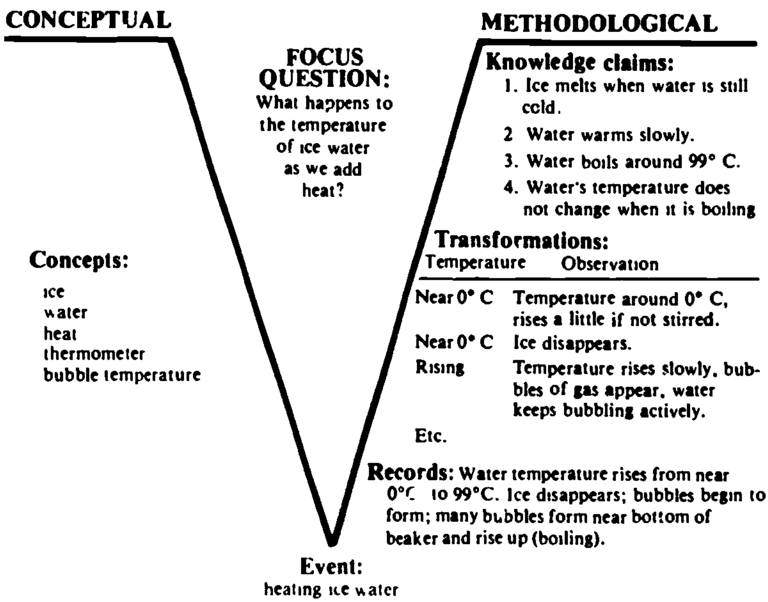


Figure 9. Vee diagram.

SOURCE: *Learning How to Learn*, by Joseph D Novak and D Bob Gowin, p 63 Copyright © 1984 by Cambridge University Press Reprinted with permission of Cambridge University Press

Working together, teachers and students can use heuristics such as the concept map and the Vee diagram to help clarify the meaning implicit in scientific investigation—meaning that escapes most students who follow directions mechanically without discovering the connection between the experiment and the idea motivating it.

THE ROLE OF STUDENT MISCONCEPTIONS: ERROR OR SIGNPOST?

A prominent feature of research in thinking is the study of student misconceptions. These are not simply errors in calculations; nor are they misapplications of strategies. They are ideas that are based on an individual misinterpretation or an incorrect generalization, and that are consistent with the student's general understanding. For this reason, they form extremely powerful barriers that must be overcome before new concepts can be learned. For example, Griffiths and Grant (71) found that high school students studying the food *web* develop misconceptions based on their understanding of the food *chain*; they do not consider that the effects of a change in one population can be passed along to other populations through several different pathways; and, thinking, in terms of food chains, they imagine that a population in a food web can affect another population only if the two have a direct predator-prey relationship.

Teachers will find it instructive to be aware of the existence and nature of the types of misconceptions prevalent among their students. Misconceptions are signposts that direct teachers and students toward problem areas, which they can then confront directly. Misconceptions can even be used as instructional aids; when a teacher presents a misconception that is troublesome for students, s/he forces them to test their conceptions against paradox and against their common sense.

While we may expect to see much new research into misconceptions appearing in education journals, the greatest resource by far is the teacher, whose laboratory is the classroom. Misconceptions are usually discovered when students have the opportunity to present them to an attentive teacher, and the pair-problem-solving classroom is the environment best suited for this dialogue. By listening to students who are actively engaged in conceptual problem solving, the teacher will uncover many misconceptions, which will provide instructional material for years to come. Sharing these discoveries with students and colleagues will contribute much toward the development of an intellectually exciting academic environment—one in which students are active participants.

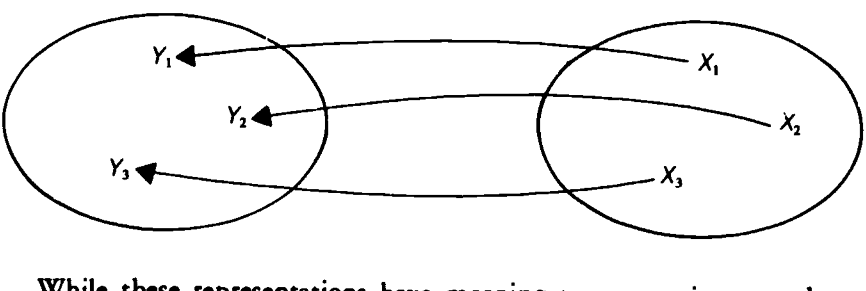
MULTIPLE REPRESENTATIONS: AN IMPORTANT INSTRUCTIONAL TOOL

Our understanding of the world comes in many forms. Although each of us thinks of reality in different ways, we are able to communicate our ideas to one another. Our communications are as diverse as our conceptualizations—yet we communicate. The structure of our communication is the manifestation of our thoughts and the substance of critical thinking. The more ways in which we can communicate our ideas, the better we can understand what those ideas consist of.

Science is the means and substance of our communicating ideas about quantitative relationships that we observe in the world. Knowledge is the representation of those ideas from the concrete (the counting of objects and the measuring of characteristics) to the very abstract (the symbolism of modern mathematics).

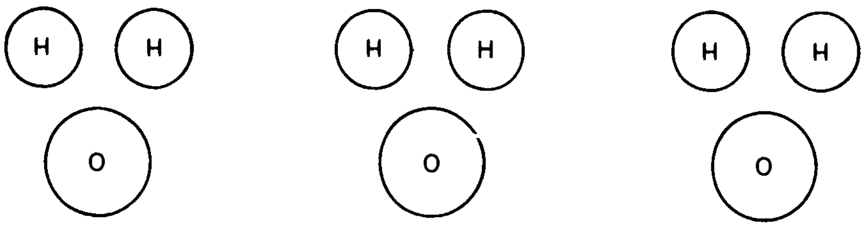
Let's consider the concept of *function*, which is basic to all science. If we were to describe our understanding of a function, we might *verbalize* the following formal mathematical definition: a function is a relationship in which no two ordered pairs have the same first component and different second components.

We might add yet another representation with the following *abstract picture*:



While these representations have meaning to us as science teachers, they are abstractions that are often beyond our students' abilities to comprehend. Fortunately, we need not stop here. We have less abstract representations to offer as well.

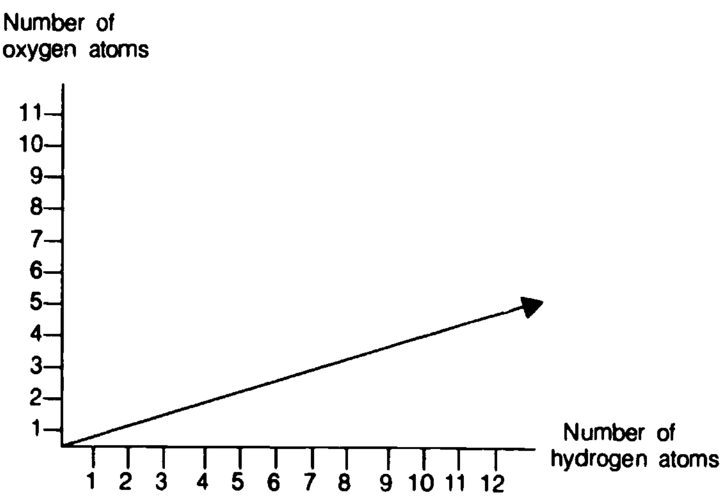
We might ask our students to consider a simple linear example. For instance, in water there are two hydrogen atoms for each oxygen atom. A *concrete picture* could look like this:



The relationship between the number of hydrogen atoms and the number of oxygen atoms can be illustrated with a *table of data*:

Number of Hydrogen Atoms	Number of Oxygen Atoms
0	0
2	1
4	2
6	3
8	4

We might also *graph* the relationship:



We might symbolize the variable quantities with letters that could be operated on to establish equality: $y = 1/2x$. Perhaps the ***equation*** is the most abstract of the representations.

Another very powerful representation is the *computer program* which serves as a model of a function machine:

Input $\longrightarrow$ Function machine $\longrightarrow$ Output

We should note that all of these representations require an *activity* on the part of the knower. Whether students are operating on quantities in an equation, plotting points on a graph, completing a data table, or formulating the calculations of a computer, they are actively representing their understanding. Critical thinking is an activity, much as representing ideas in science is an activity.

Our tasks are to familiarize our students with the many ways of representing their understanding and to encourage them to use those representations to solve problems. Besides promoting critical thinking, we can expect the following benefits:

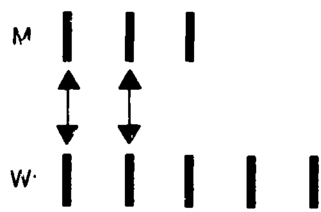
- Representing the problem is a catalyst for problem solving. It gets the student started.
- Concrete representations encourage the students by demonstrating their understanding of the problem to themselves and to their teacher.
- Similarly, using student representations serves as a pedagogical aid for teachers. It enables teachers to anchor their lessons with what their students already understand. Instruction can then be geared toward the extension of concepts through multiple representations that are often generated by the students.
- Multiple representations enable students to appreciate the complexity and richness of scientific reasoning and the variety of solutions.
- Likewise, our students inform us of new ways to conceptualize a problem.

To illustrate the last point, consider the following student solution to a problem using ratio concepts as well as fractions.

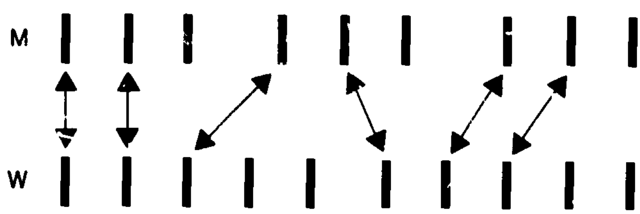
In a certain population 2/3 of all men are married but only 3/5 of all women are married. What fraction of the population is single?

Without using (or knowing) algebra, the student reasoned with the following picture:

Assuming that the men are married to the women, I can match them up Let's let the men and women walk into a room. So, when every three men come in, two of them are married, and when every five women walk in, three of them are married



But there is one woman who needs to be matched, so I need another group of men. In fact, I'm going to enter groups of men and women until everybody who needs a mate has one.



That does it. Now everyone is matched. There are 19 people in the room and 7 of them are single so the fraction of the population that is single is 7/19.

The simplicity and ingenuity of this solution are striking. It is the type of solution that one would like to have thought of oneself.

As teachers, we should not only encourage our students to use representations, but we should also model the use of representations in our own problem solving. Pictures, verbal descriptions, data tables, graphs, and equations all serve as representations.

Here are some examples of qualitative graphing—problems that require no numbers or measurements:

1. Write the story of the race between the tortoise and the hare. Then graph the distance versus time of the race as well as the speed versus time of the race.
2. Graph the height versus time of a ball bounced on the floor. Also, graph the speed versus time.
3. Graph the time of sunrise for one year.
4. Graph P = Number of turns of the pedal versus W = Number of turns of the wheel. (In a single gear; assume W is greater than P)
5. Graph S = Number of sides in a regular polygon versus D = Number of diagonals that can be drawn from a single vertex V.
6. Graph H = Estimated number of heads expected versus T = Total number of times a coin is tossed.
7. As you play with a yo-yo, the yo-yo's distance from the floor changes with time. Graph this change.

THE LABORATORY: A PLACE WHERE STUDENTS CAN MAKE DISCOVERIES

Most middle school and high school laboratory experiences are fairly mechanistic: students follow a manual step-by-step and arrive at an anticipated result. However, student laboratory experiences *can* be inquiry-oriented, and when they are, they add to how students think about the experiment before them and, by extension, the world around them.

In an example from physics, the following circles laboratory was designed to expose students both to tabular and graphical representations and to the discovery of pi. The equation that relates the circumference to the diameter is intended to be a surprising and enlightening final representation in the lab.

Instructions:

Your lab kit includes a number of circles and a tape measure. Measure the diameter and circumference of each of the five circles and fill in the appropriate sections of the data sheet on the next page. Next, fill in the rest of the data sheet by making the calculations indicated in the column headings. Now, set up scales on the graph paper for the circumference and the diameter and, for each circle, plot a point on the graph paper. Connect the points you have plotted.

YOU HAVE NOT COMPLETED THIS LABORATORY UNTIL YOU HAVE ANSWERED *ALL* OF THE QUESTIONS BELOW

Look very carefully at your data table and your graph before you try to answer the following questions.

1. Make a statement about circles that you believe to be true for *all* circles, even those much bigger or smaller than the ones you measured.
2. Can you justify the conclusion you drew above from the data you collected? If so, how?
3. From the work you have done in this lab, write down a mathematical equation that is true for all circles.
4. You have information displayed in two forms: the data sheet and the graph. On which form do you find the most information? Why?
5. Does the information displayed in either form tell you what to expect in the other form? If so, how?

THE SCIS LEARNING CYCLE: EXPLORATION, INVENTION, DISCOVERY

Developed by Robert Karplus and others for the Science Curriculum Improvement Study (20), the Learning Cycle deliberately incorporates features of Swiss psychologist Jean Piaget's theory of the development of intellect. Piaget offered a convincing argument that intellect is not genetically determined and static, but rather it develops in stages that proceed from the perception of concrete objects to the formal reasoning involved in the formation and interpretation of concepts. Studies have shown that 50 percent of the population between the ages of 14 and 60 primarily uses concrete reasoning patterns—i.e., they have difficulty with the type of formal reasoning needed to understand most math and science concepts (4).

The Learning Cycle engages students in a reasoning process that proceeds from concrete observations toward the articulation and evaluation of concepts. According to Arons, the formation of physical concepts ought to proceed from "concrete experience, careful development between observation and inference, necessity of control of variables, arithmetical reasoning involving division, inductive and deductive reasoning in working with theoretical models, making initial steps from hypothetical-deductive reasoning, and at all times maintaining conscious awareness of one's own thought processes" (4).

The framework of the Learning Cycle calls for three steps in the development of lesson plans to help facilitate concept acquisition and higher-order thinking:

1. *Exploration:* This first phase generally takes the form of a demonstration or experiment with accompanying questions that ask for a description of what is observed, coupled with qualitative analysis from students.

2. *Invention:* This step calls for the introduction of technical language that defines the analysis completed in the exploration. Formulas and algorithms may be derived and explicitly stated while

constantly being connected to students' own observations and conjectures.

3. *Discovery:* Lastly, students need to apply the concept outlined above in order to fully understand the meaning of both that concept and whatever formalism that has been described. This phase almost always takes place within the context of problem solving.

Two examples of the Learning Cycle follow, one from the physical sciences and one from the biological sciences.

Let's first consider a chapter entitled "Batteries and Bulbs" from Arons's book *The Various Language: An Inquiry Approach to the Physical Sciences* (4). Arons begins the exercise with an *exploration* into the configurations of wire, battery, and bulb that result in the successful lighting of the bulb. The experiment is modified by interposing different materials—paper, coins, fingers, pencils, keys, glass, etc.—into the configuration. Additional exploration occurs as students examine the inside of a battery and the inside of a light bulb. Because switches, sockets, and more bulbs and batteries are included, students have ample opportunity to explore a number of conjectures that result from questions about their observations. Some of the types of questions asked by Arons follow:

- Why is the word "circuit" appropriate in describing your observations?
- Which materials result in an open or closed circuit when interposed in the circuit? How would you classify air in this context? Upon examining the inside of a light bulb; in what portion of the bulb does the light originate?
- What is the purpose of a switch? How does it work? (4)

Subsequent to this exploration, Arons *invents* a model of electric current in which technical terms—such as *current, flow, conductors, nonconductors, electric battery, circuit, direction of flow, resistance, volts, parallel,* and *series circuits*—are introduced and defined. To this, Arons also adds descriptions of conventional symbols for circuit diagrams, together with questions about the circuits described by the diagrams. The use of multiple representations is necessary to ensure effective use of class time, as well as to provide a more powerful means of communication.

To facilitate the *discovery* phase of the Learning Cycle, Arons asks questions that challenge students at a conceptual level. Consider some of the following questions that appear at the end of the unit:

> You have frequently heard the term "short circuit" used in connection with electrical systems. What does it mean? Identify among the experiments you have performed those that involved short circuits . . .
>
> Describe, both in terms of actual observations and in terms of the current model, what happens when you connect a bulb to a battery and then short-circuit the battery by connecting a wire across the terminals.
>
> Does our model predict that the current will be zero in the bulb under these circumstances or merely relatively small? Justify your answers. . .
>
> Do switches, sockets, and bulbs have nonconducting material present in their structure? If nonconducting material is present, what role does it play? What would happen if it were not there? . . .
>
> What hints and information might nature be conveying via our observations that fixed proportions of hydrogen and oxygen are liberated at the two electrodes in the electrolysis experiment [a previous experiment in the course]? (4)

Arons's text contains many units with a similar organization and hundred of problems that elicit conceptual understanding from students.

Some excellent biology curriculums have been prepared by education researchers (23, 24, 25, 41). Most of this work either was written with the Learning Cycle in mind or can be readily adapted. Lawson (24) describes an activity based on those of Stebbins and Allen (41) that instructs students in the concept of natural selection:

1. *Exploration:* The teacher distributes over a wide grassy area about 400 toothpicks—one-third painted green, one-third painted yellow, and one-third painted red—after recording the exact number of each. Students are then asked to pretend that they are toothpick-insect-eating birds and are given five minutes to hunt for as many toothpick insects as they can find. Back in the classroom, the toothpicks are classified according to color and counted, with percentages calculated. The students are asked, "What color insect would you rather be if you had a choice?"
2. *Invention:* The teacher introduces the term ***natural selection*** to describe the process of differential selection of . particular color of toothpick insect. Lawson also suggests that the students read "Darwin's Missing Evidence" (22), an article by Kettlewell that discusses the cause of industrial melanism and that provides the basis for discussion of such concepts as *geologic time*, *biotic*

potential, *limiting factors*, *variation*, *heredity*, and *natural selection*.

3. *Discovery:* Lawson suggests the use of questions that stimulate students' imaginations and test their conceptual understanding:

   > How do you think these processes affect human beings today? Are we still evolving? If so, in what direction? Why was DDT so effective in killing mosquitoes when it was first introduced? Why did it become less effective to their present forms? (24)

The Learning Cycle is recommended to teachers of all subjects. Using the developmental theories of Piaget, this method moves students from concrete operational thought to formal operational thought, where critical thinking is most apparent. It is also extremely compatible with other instructional methods discussed in this book.

CLASSROOM MANAGEMENT ISSUES

Many of the suggestions in this monograph involve student-centered, as opposed to teacher-centered, activities. In this section, we will discuss some of the classroom management issues raised when this different classroom structure is used.

Teaching thinking skills in the science classroom means activating the learner. Thus, even during teacher-directed activities, there should be ample room for students' responses. For example, consider this phenomenon that occurs in the recitation class: the teacher asks a question, does not get a quick response from students, and ends by answering his/her own question. Tobin (43) studied 20 sixth and seventh grade classrooms in which science teachers were giving lessons related to probabilistic reasoning. Each lesson involved a materials-centered problem to be solved by students. Probabilistic concepts were introduced and applied through planning how to solve the problem, collecting data, and interpreting the results. During the subsequent classroom discussion, teachers in 10 of the classes were instructed to give students 3 to 5 seconds to respond to problems or questions. Significant positive effects resulted from this extended wait-time: students' responses were longer, and teachers' responses to student comments tended to probe for more student input, rather than simply restating students' responses. That is, the discussion reached a higher level and exhibited more true give-and-take than in the control classes. Finally, students in the extended wait-time classes performed better on end-of-unit tests than did their peers in the control groups: more active classrooms produce more student learning.

As Tobin notes, there are times in all science classes when whole-class activity is necessary. Here are his suggestions for activating student learning during whole-class activities through extended teacher wait-time:

1. A question is clearly presented at a relevant time during the lesson.
2. All students are given 3 to 5 seconds of silence in which to consider a response.
3. One student is called on to respond to the question

4. The student is provided 3 to 5 seconds to commence a response before the question is repeated, rephrased, or redirected to another student.
5. After a student has responded to a question, 3 to 5 seconds are provided for the student to commence to elaborate or evaluate the appropriateness of the response.
6. The question or the response is redirected to another student in the class. (43, p. 789)

Tobin notes that there are *fewer* statements made in classrooms in which teachers use this method, but that the level of discussion is higher, with greater student input—and, as we noted—more learning, as measured by summative test performance.

This principle applies to learning from experiments as well. Okebukola (32) found that students do not develop practical laboratory skills through *teacher* modeling and information transmission: what is needed is increased time for students to observe and record data.

In the same vein, overprompting students by giving them strong hints as to the answers to questions can have detrimental effects on student learning. Holliday (15) gave tenth grade biology students a complex diagram with related questions to help students interpret the diagram. Some students were also given strong hints about the answers to the questions: for example, the number of a question might be placed next to the part in the diagram that answered the question. Not surprisingly, those students who had to examine the diagram closely for the answers learned more than the students in the control group who simply matched up the numbers in rote manner.

Because science students are working individually and in pairs on materials-based projects, there is perhaps greater opportunity for disruptive behavior than in classes in other content areas. Using student behaviors (both on-task and disruptive) as the criteria for classroom management effectiveness, Sanford (38) examined teachers' management methods in 26 junior high school classrooms. She found that students were more likely to be on task in classrooms in which the teacher responded to minor disruptions *early*. Sanford's study shows other areas of cl oom management that are critical to effective science classrooms. In ticular, consistent enforcement of rules and well-organized student work procedures are important. Teachers should make work requirements clear, monitor student progress on assignments (giving students feedback on their work), and frequently check daily work and quizzes in class. Beasley (5) found that high school students were more likely to be on task during laboratory periods when the teacher spent *brief* periods of time with pairs or groups of students and was available to respond quickly to small disruptions when they occurred. By contrast, Beasley found that students were more disruptive in classrooms in which teachers spent considerable time with each small group: students in other parts of the classroom could begin nontask activities that might erupt into disruptive incidents. We have found that the most effective teachers are those who find the balance between the constant attention needed to maintain discipline and the individual attention required for listening to students thinking aloud. Teacher-student interaction must be at least one minute to have any important effect, and could last as long as ten minutes. During the longer interaction, an occasional glance around the classroom does much to keep students on task. Although some students may not be monitored on any given day, all students should receive individual (small group) attention at least twice a week. Optimally, the teacher should form a case history for each student.

CONCLUSION

The effectiveness of a science program is determined by the ability of students to better understand the type of thinking that science entails. Students need to develop effective strategies for learning that go beyond the rote memorization of formulas matched to sample problem-types. Conceptual understanding must be seen as the goal of science instruction—a goal that can be realized through solving conceptual problems and completing exercises that develop interpretation and representation skills.

The self-conscious reflection about one's own thoughts and ideas is the essence of metacognition. It is a necessary condition for effective problem solving, and it is facilitated through oral and written communication of thinking as-it-happens. The clinical interview employed in research on thinking processes is perhaps the best available model of critical thinking Teaching students to work in pairs, reasoning aloud and interviewing each other so as to understand the thought processes of the problem solver, is one effective means of developing critical thinking skills and conceptual understanding in science. Integrating process skills into the curriculum, as well as providing activity-based instruction, will make students more active learners. At all levels of science instruction, helping students to generate questions—to raise and test hypotheses about the world around them—is vital to scientific thinking. Using heuristics and making multiple representations of concepts and problems will also improve students' understanding of science. And, through the Learning Cycle of exploration, invention, and discovery, teachers can encourage students to explore and describe their own ideas—and to convince themselves, their peers, and their teachers of the effectiveness of those ideas. Ultimately, the focus of instruction is on the *process of gaining knowledge*, rather than on the objects of knowledge.

BIBLIOGRAPHY

1. Allen, Leslie R. "An Evaluation of Certain Cognitive Aspects of the Material Objects Unit of the Science Curriculum Improvement Study Elementary Science Program." *Journal of Research in Science Teaching* 7 no. 4 (1970): 277-81.
2. American Association for the Advancement of Science, Commission on Science Education. *Science—A Process Approach*. New York: Xerox Education Division, Parts A–C, 1967; Parts D–E, 1968.
3. Arons, Arnold B. "Thinking, Reasoning, and Understanding in Introductory Physics Courses." Paper presented at meeting of Groupe International de Recherche se L'enseignement de la Physique, Weizman Institute of Science, Rehovot, Israel, August 19-24, 1979.
4. ______. *The Various Language: An Inquiry Approach to the Physical Sciences*. New York: Oxford University Press, 1977.
5. Beasley, Warren. "Teacher Management Behaviors and Pupil Task Involvement During Small Group Laboratory Activities." *Journal of Research in Science Teaching* 20, no. 8 (1983): 713-19.
6. Boyd, M. E. "A Study to Determine the Effects of Science Inquiry on the Abstract Categorization of Deaf Children." *Dissertation Abstracts* 74 (1970): 137-65.
7. Bredderman, Ted. "Effects of Activity-Based Elementary Science on Student Outcomes: A Quantitative Synthesis." *Review of Educational Research* 53, no. 4 (1983): 499-518.
8. Carmicheal, J. W., and Bauer, Joanne, Sr. "Cognitive Teaching in the Chemistry Classroom." *Journal of Learning Skills* 1, no. 2 (1982): 27-30.
9. Dillashaw, F., and Okey, James R. "Test of Integrated Science Process Skills for Secondary Science Students." *Science Education* 64 (1980): 601-608.
10. Gray, R L. "Toward Observing That Which Is Not Observable." In *Cognitive Processes Instruction*, edited by J. Lochhead and J. Clement. Philadelphia: Franklin Institute Press, 1979.
11. Griffiths, Alan K., and Grant, Bette A. C. "High School Students' Understanding of Food Webs: Identification of a Learning Hierarchy and Related Misconceptions." *Journal of Research in Science Teaching* 22, no. 5 (1985): 421-36.
12. Heiman, Marcia. "Learning to Learn." *Educational Leadership* 43, no. 1 (1985): 20-24.
13. Heiman, Marcia, and Slomianko, Joshua. "Learning to Learn: Some Questions and Answers." Cambridge, Mass.: Learning Associates, 1984. (Available from Learning Associates, Box 493, Cambridge, MA 02138.)

14. Hestenes, David. "Wherefore a Science of Teaching?" *The Physics Teacher* (April 1979).
15. Holliday, William G. "Overimprinting Science Students Using Adjunct Study Questions." *Journal of Research in Science Teaching* 20, no. 3 (1983): 195-201.
16. Horton, Phillip B., Fronk, Robert H.; and Walton, Raymond W. "The Effect of Writing Assignments on Achievement in College General Chemistry." *Journal of Research in Science Teaching* 22, no. 6 (1985): 535-41.
17. Hunter, Jacqueline, and others. "Project SOAR: Teaching Cognitive Skills in a Pre-College Program." *Journal of Learning Skills* 1, no. 2 (1982): 24-26.
18. Inhelder, B., and Piaget, J. *The Growth of Logical Thinking from Childhood to Adolescence*. New York: Basic Books, 1958.
19. Johnson, Virginia, ed. *Biological Science: Patterns and Processes*. Biological Sciences Curriculum Study. New York: Holt, Rinehart, and Winston, 1965.
20. Karplus, R. *Science Curriculum Improvement Study*. Teacher's Handbook. Berkeley: University of California, 1974.
21. Karplus, R.; Karplus E.; and Wollman, W. "Intellec .! Development Beyond Elementary School IV: Ratio, The Influence of Cognitive Style." *S-hool Science and Mathematics* (October 1974).
22. Kettlewell, H. B. D. "Darwin's Missing Evidence." *Scientific American* .'00, no. 3 (1959): 48. (Offprint 842)
23. Lawson, A. E. "An Activities Approach to Natural Selection." In *Educators' Guide to Free Science Materials*. Randolf, Wis.: Educators Progress Service, 1973.
24. ______. "Developing Formal Thought Through Biology." *American Biology Teacher* 37 (1975): 411-20.
25. Lawson, A. E., and Renner, J. W. "Piagetian Theory and Biology Teaching. *American Biology Teacher* 37, no. 6 (1975): 336.
26. Linn, M. C., and Rice, M. "A Measure of Scientific Reasoning: The Springs Task." *Journal of Educational Measurement* 16 (1979): 55-58.
27. Lochhead, J. "An Anarchistic Approach to Teaching Problem Solving." *Journal of Learning Skills* 1, no. 2 (1982): 3-11.
28. Lochhead, J., and Clement, J., eds. *Cognitive Process Instruction*. Philadelphia: Franklin Institute Press, 1979.
29. Lord, Thomas R. "Enhancing the Visuo-Spatial Aptitude of Students." *Journal of Research in Science Teaching* 22, no. 5 (1985): 395-405.
30. Morgenstern, Carol F., and Renner, John W. "Measuring Thinking with Standardized Science Tests." *Journal of Research in Science Teaching* 21, no. 6 (1984): 639-48.
31. Novak, Joseph D., and Gowin, D. Bob. *Learning How to Learn*. Cambridge, England: Cambridge University Press, 1984.

32. Okebukola, Peter A. "Science Laboratory Behavior Strategies of Students Relative to Performance in and Attitude to Laboratory Work." *Journal of Research in Science Teaching* 22, no. 3 (1985): 221-32.
33. Padilla, Michael J. "Science Activities—for Thinking." *School, Science, and Mathematics* 80 (1980): 601-608.
34. Padilla, Michael J.; Okey, James R.; and Garrard, Kathryn. "The Effects of Instruction on Integrated Science Process Skill Achievement." *Journal of Research in Science Teaching* 21, no. 3 (1984): 277-87.
35. Resnick, Lauren. "Education and Learning to Think." A special report prepared for the Commission on Behavioral and Social Science and Education, National Research Council, 1986.
36. Rodriguez, Imelda, and Bethel, Lowell J. "An Inquiry Approach to Science and Language Teaching." *Journal of Research in Science Teaching* 20, no. 4 (1983): 291-96.
37. Rowell, J. A., and Hoffman, P. J. "Group Tests for Distinguishing Formal from Concrete Thinkers." *Journal of Research in Science Teaching* 12 (1975): 157-64.
38. Sanford, Julie P. "Management and Organization in Science Classrooms." *Journal of Research in Science Teaching* 22, no. 3 (1985): 221-32.
39. Sayre, S., and Ball, D. W. "Piagetian Cognitive Development and Achievement in Science." *Journal of Research in Science Teaching* 12 (1975): 165-74.
40. *Science Curriculum Improvement Study*. Boston: D.C. Heath, 1966.
41. Stebbins, R. C., and Allen B. "Simulating Evolution." *American Biology Teacher* 37, no. 4 (1975): 206.
42. Tobin, Kenneth. "Effects of Extended Wait Time on Discourse Characteristics and Achievement in Middle School Grades." *Journal of Research in Science Teaching* 21, no. 8 (1984): 779-91.
43. ______. "Student Task Involvement in Activity Oriented Science." *Journal of Research in Science Teaching* 21, no. 5 (1984): 469-82.
44. Tobin, Kenneth, and Capie, W. "Teaching Process Skills in the Middle School." *School, Science, and Mathematics* 80 (1980): 590-600.
45. University of California. "Science Teaching and the Development of Reasoning." Berkeley, Calif.: The University, Lawrence Hall of Science, n.d.
46. Whimbey, A., and Lochhead, J. *Beyond Problem Solving and Comprehension*. Hillsdale, N.J.: Lawrence Erlbaum Associates, 1984.
47. ______. *Problem Solving and Comprehension*. Philadelphia: Franklin Institute Press, 1980.