Reading and Writing to Learn Science: Achieving Scientific Literacy

Shawn M. Glynn and K. Denise Muth

University of Georgia, Athens, Georgia 30602

Abstract

A key step in helping students to achieve scientific literacy is to ensure that each school's curriculum supports students' efforts to learn science meaningfully. Educational researchers play a vital role in this step by providing teachers, teacher educators, administrators, and policy makers with information about the creation of a curriculum that supports scientific literacy. In a scientific literacy curriculum, reading and writing can serve as dynamic vehicles for learning science meaningfully. The task of educational researchers is to show how reading and writing can be used most effectively to support science learning. Much of what is done now in schools is based on teacher intuition—good intuition—but intuition nonetheless. What is needed is school-based research to validate and build upon these intuitions. This article is intended to stimulate research on reading and writing to learn science.

In the 21st century, science will have a dramatic impact on the quality of personal lives, on the environment, and the world economy. To prosper in this new century, our students—all of them—must become scientifically literate and embrace the notion of lifelong learning in science.

Defining Scientific Literacy

What does it mean to be scientifically literate? According to the American Association for the Advancement of Science (AAAS) report, Science for All Americans (1989), the scientifically literate person is:

... one who is aware that science, mathematics, and technology are interdependent human enterprises with strengths and limitations; understands key concepts and principles of science; is familiar with the natural world and recognizes both its diversity and unity; and uses scientific knowledge and scientific ways of thinking for individual and social purposes. (p. 4)

Utilizing this definition as a basis for judgments, many of our students, perhaps most of them, are not scientifically literate. As well, a disproportionate share of these students are females and minorities. This problem extends beyond students to parents and other role models. In an editorial in the American Scientist (Miller, 1988), only 5% of the United States population was estimated to be scientifically literate. Without scientific literacy, it is difficult to make
informed decisions about the interrelated educational, scientific, and social issues that one
confronts every day in the newspapers. For example, "California City Considers Creationism
Teaching" is the headline of a recent Los Angeles Times article that reports:

Vista, Calif.—A nationally watched debate that may ultimately be resolved by the Su-
preme Court has captivated this normally quiet San Diego County community, as a
Christian majority on the city's education board moves toward a policy mandating the
teaching of creationism in public schools. (Granberry, 1993, p. 2a)

Students must become scientifically literate in order to make informed decisions on issues as
important as this and, as this issue illustrates, scientific literacy involves more than just science
knowledge. To be scientifically literate, students also must have the reading ability to evaluate
the print-based information presented to them, and the writing ability to communicate their
thoughts to others and have an impact on their thinking (Holliday, Yore, & Alvermann, 1994).

As early as the elementary and middle grades, students begin losing interest in science. By
high school, students of all achievement levels find science hard, dull, and meaningless. As a
consequence, scientific literacy suffers and United States students compare poorly with those of
other industrialized nations.

Achieving Scientific Literacy

How do science educators and researchers help students achieve scientific literacy? Teach-
ing more science facts to the students is not the answer. Increasing the number of students’
laboratory activities is not the answer either. A trendy emphasis on hands-on activities will not,
by itself, increase students’ scientific literacy. What is additionally needed is a “minds-on”
emphasis in the learning of science. The importance of being able to understand and explain—in
clear language—the meaning of fundamental scientific concepts is central to science literacy.
Famous scientists often address this point. For example, Nobel laureate Erwin Schrödinger
(1951, pp. 7–8) wrote of his work in quantum physics: “If you cannot—in the long run—tell
everyone what you have been doing, your doing has been worthless.” Along similar lines,
Werner Heisenberg (1958, p. 168) wrote: “Even for the physicist the description in plain
language will be a criterion of the degree of understanding that has been reached.” Finally, a few
years ago, during U.S. President George Bush’s term of office, the then National Science
Foundation director, Walter Massey (1989, p. 920), wrote to the President:

I would suggest that you appoint no one as your science adviser who cannot explain to you
in a language you can understand the important scientific and technological issues that will
confront you. Anyone who says “It is too technical for me to explain to you” should be
replaced immediately.

By their very nature, reading and writing activities can play a vital role in achieving a minds-on
emphasis in the learning of science. Reading and writing activities can serve as conceptual tools
for helping students to analyze, interpret, and communicate scientific ideas (Holliday et al.,
1994). These activities can help engage in students’ minds the complex reasoning and problem-
solving processes that scientists use in the course of their work.

A Model of Students’ Cognitive Processes

To understand the role that reading and writing can play in the learning of science, it is
helpful to formulate a model of a student’s cognitive processes (see Figure 1). This model is
based on a computer analog and includes the following components: (a) perception, (b) working memory, (c) long-term memory, and (d) metacognition. The metacognitive component represents the awareness and control of all the cognitive processes. Visual, auditory, or tactual information is perceived and then processed in working memory, where higher order learning operations are carried out and intellectual "products" (e.g., hypotheses, inferences, generalizations, elaborations, and solutions) are formed. The products are formed in working memory using information and skills retrieved from long-term memory; scientific information and science process skills, as well as reading and writing skills, are part of long-term memory. In this model, the science process skills, reading skills, and writing skills are dynamic and interactive components. They are carried out concurrently in working memory.

Working memory is like RAM and a screen on a computer monitor, in that current operations (i.e., what one is reading or writing at a given point in time) are displayed on that screen. Working memory is limited in terms of how much information it can deal with at one time, just as the screen is limited in terms of how much it can show at one time. Long-term memory has an enormous capacity for storing categorized, hierarchically organized information, just like the hard disk of a computer.

This model departs from the computer analogy in an important way: The perception, storage, and retrieval of information are all constructive processes, not rote processes. The students' expectations, beliefs, values, sociocultural background, and existing knowledge have an influence on the processing of information. What students construct determines what they learn. As a result, no two students learn exactly the same thing when they read a science textbook, listen to a lesson, observe a demonstration, write a report, or do a laboratory activity.

This model departs from the computer analogy in yet another way: the role played by practice and cognitive strategies. By practicing procedural skills (e.g., reading, writing, and science process skills) and declarative knowledge (e.g., science vocabulary) to the point of
automaticity, students can more effectively conserve the limited capacities of their working memories, as well as retrieve information more effectively from their long-term memories. The relatively specific model of students' cognitive processes described here is consistent with more general models of cognitive architecture (Anderson, 1990; Britton, Glynn, & J. Smith, 1985; Case, 1993; Gagne, 1985) and will be used throughout this article as an explanatory tool in discussing the roles of reading and writing in learning science.

Learning Science Constructively Through Reading and Writing

Meaningful learning is the process of actively constructing conceptual relations between new knowledge and existing knowledge (Glynn, 1991; Glynn, Yeany, & Britton, 1991). Conceptual relations in science are of many kinds, including hierarchical, enumerative, exemplifying, sequential, comparative, contrasting, causal, temporal, additive, adversative, and problem solving (e.g., Mayer, 1985; Spiegel & Barufaldi, 1994). Relations of these kinds are woven into well-written scientific text.

Students should learn concepts as organized networks of related information, not as lists of facts. Science teachers realize this, of course, but are not sure how to facilitate relational learning in their students, particularly when the number of students in a class is large and the concepts are complex; and complex concepts are the rule rather than the exception in biology (e.g., photosynthesis and mitosis–meiosis), chemistry (e.g., chemical equilibrium and the periodic table), physics (e.g., gravitational potential energy and electromagnetic induction), earth science (e.g., plate tectonics and precipitation), and space science (e.g., the sun and planetary motion). In one form or another, many of these concepts are introduced to students in the elementary school years; by high school, all students are expected to be scientifically literate and to understand these complex concepts.

By reading well-written scientific text and by endeavoring to write it, students familiarize themselves with the conceptual relations that form the basis of real scientific expertise and understanding. For this reason, reading and writing activities are ideal media for engaging students' minds and for fostering the construction of conceptual relations. Students who are learning constructively will challenge the science text they are reading or writing, struggle with it, and try to make sense of it by integrating it with what they already know.

Reading to Learn Science

Learning to read prepares a student for reading to learn. According to the directors of the National Reading Research Center:

The ability to learn from subject matter textbooks and other print materials is a mark of one's independence as a literate person. This ability also signifies that one is able to think critically and draw reasonable conclusions about the information presented in textbooks or other media. (Alvermann & Guthrie, 1993, p. 5)

Students who learn from subject matter textbooks and other print materials rely upon their previously learned science knowledge and science process skills stored in long-term memory (Figure 1). The distinction between science knowledge and science process skills, or thinking skills, has been and continues to be an important one in science education (Carey & C. Smith, 1993; Dunbar & Klahr, 1989; Inhelder & Piaget, 1958; Kuhn, Amsel, & O'Loughlin, 1988). Science knowledge should be understood in ways that will enable it to be used. The science process skills are those routinely performed by practicing scientists in many disciplines. In the
report *Science for All Americans* (AAAS, 1989), the science process skills were identified as (a) computational, (b) estimation, (c) manipulation, (d) observation, (e) communication, and (f) critical response. All of these skills are important, but for present purposes, communication and critical response are particularly important and merit further explanation.

Communication skills are essential because “discourse in science, mathematics, and technology calls for the ability to communicate ideas and share information with fidelity and clarity, and to read and listen with understanding” (p. 138). Critical-response skills are essential because:

In various forms, the mass media, teachers, and peers inundate students with assertions and arguments, some of them in the realm of science, mathematics, and technology. Education should prepare people to read or listen to such assertions critically, deciding what evidence to pay attention to and what to dismiss, and distinguishing careful arguments from shoddy ones. (p. 139)

Communication, critical response, and the other science process skills should be activated and refined in authentic, real-world contexts. Reading activities can provide these contexts and ensure that the learning is constructive in nature rather than rote.

Students who are competent readers can retrieve from long-term memory a variety of powerful component skills to facilitate comprehension. These component skills are dynamic, interactive, and carried out concurrently in students' working memories. The skills include metacognition, word recognition (through matching or sounding out), lexical access (retrieving word meanings), semantic and syntactic analysis (parsing), integration (of sentences), inference (predictions), identification of text relations (patterns), summarization (gist), and elaboration (connecting new and existing information). These skills are consistent with those specified in general reading-comprehension models (e.g., Collins & E. Smith, 1982; Just & Carpenter, 1987; Kintsch, 1986; Kintsch & van Dijk, 1978). Although all of these skills are critical, metacognition plays a particularly important role in reading science text.

Metacognition is “thinking about your thinking as you are thinking to improve your thinking” (Yore, Craig, & Maguire, 1993, p. 1). It involves setting goals for what one wants to learn from the text and identifying strategies to help one achieve those goals (Yore et al., 1993). Metacognition also involves checking one's goals during text reading to ensure that they are being met and, if they are not, taking remedial action. By bringing reading skills and science process skills concurrently to bear on existing knowledge and new knowledge in the text, students' construct a representation of the text's meaning in their working memory (Kintsch, 1986). This constructed representation has the advantage of being meaningful to students and, therefore, more memorable and applicable. At the same time, this mental representation may incorporate reasonable misconceptions about the ideas expressed in the text. The formation of reasonable misconceptions is a normal consequence of meaningful learning. Reasonable misconceptions result when students construct new knowledge by integrating existing knowledge with that in the text (Hynd, McWhorter, Phares, & Suttles, 1994). Misconceptions could be avoided through rote learning, but this kind of learning is neither memorable nor applicable.

**Textbook Versus Teacher-Driven Curricula**

Students with good science process skills and reading skills are well on their way to achieving scientific literacy; however, the attainment of literacy also presupposes effective instructional methods, textbooks, and print materials. School science curricula can be placed on a continuum from textbook-driven to teacher-driven. In a textbook-driven curriculum, the
A textbook-driven curriculum aspires to be "teacher-proof" or able to support teachers who may lack important knowledge, training, and experience. The science curriculum of the United States tends to be textbook-driven. Publishers refer to their product as a "program" rather than a textbook, because the teacher's edition prescribes precisely how concepts should be taught, and the textbook is accompanied by a host of resource materials, such as videotapes, software, overhead transparencies and masters, laboratory manuals, study guides, test item banks, posters, and motivational activities (e.g., science fairs and competitions). The textbook guides the teacher in the selection of topics, the organization of lessons, the assignment of activities, and the construction of tests.

In a teacher-driven curriculum, a textbook may still play an important role, but as a reference rather than a curriculum guide. The teacher is empowered and has much more control over the instructional methods and the use of other print-based materials, such as trade books, magazines, and biographies of scientists. The teacher-driven curriculum assumes that the teacher knows a great deal about science, about methods of instruction, and about the basic skills of reading and writing.

Reading Activities and Strategies

Learning from science textbooks and other print-based materials should be meaningful, conceptually integrated, and active: Passive, isolated, rote learning is boring, easily forgotten, and inapplicable (Alexander & Kulikowich, 1994; Glynn & Britton, 1984). To comprehend fundamentally important concepts in science textbooks, students need activities and strategies that support active, process-oriented learning (Norris & Phillips, 1994; Pressley, Borkowski, & Schneider, 1990). Some possible activities for learning science include asking students to read the following:

1. Newspaper stories about new developments in science and technology. Excellent stories also can be found in magazines, such as Science News, National Geographic, Natural History, Discover, and Smithsonian.
2. Trade books on a variety of science topics.
3. Different textbooks as references, comparing their explanations of topics.
4. Biographies of scientists, particularly of those from groups that have been traditionally underrepresented in science.
5. The award-winning prose of scientists, such as Lewis Thomas (1974), author of The Lives of a Cell.
6. Highly acclaimed science fiction stories, such as those written by Isaac Asimov and Arthur C. Clarke.

The preceding activities, combined with content-oriented reading strategies, are ideal for learning science. There are a number of strategies that reading educators have developed to facilitate students' comprehension and memory of a text. One of the most enduring is SQ4R (E.L. Thomas & H.A. Robinson, 1972), which is itself an elaboration of an earlier strategy, SQ3R (F.P. Robinson, 1961). The SQ4R strategy teaches students to attack a content area text in a series of sequential steps. The steps in the SQ4R strategy are presented in Table 1. There is a great need for research to validate the effectiveness of SQ4R in learning from science text. It is also important to examine the relative contributions of the individual steps in the strategy. The few studies that have been conducted, such as that of Adams, Carnine, and Gersten (1982) with fifth-grade students, have shown the strategy to be very effective in improving students' immediate and delayed recall of text.
Another content-oriented reading strategy is MURDER (Dansereau, 1985). As can be seen in Table 1, MURDER is a bit more complicated and specific than the SQ4R strategy. Dansereau demonstrated that MURDER training improved college students’ text recall by 30 to 40%. Just as important, those students reported 3 months after training that they were still using the strategy and were quite satisfied with it. Like SQ4R, there is a need for further research with MURDER to examine the relative contributions of its component steps.

Still another content-oriented reading strategy is reciprocal teaching (Palincsar, 1986; Palincsar & Brown, 1987). This strategy is intended to help students monitor their own comprehension. Reciprocal teaching does this by making the steps in the comprehension-monitoring process overt and explicit. As can be seen in Table 1, there are four sequential steps students apply to each paragraph in the text they are reading. If the students can successfully fulfill the steps, they can go forward; if not, they should reread the text. It is important for teachers to model the strategy for students, using techniques such as thinking out loud and providing the students with regular feedback. When the students have internalized and automatized the strategy, they assume progressively more responsibility, eventually assuming the role of the teacher in reading and discussing the text with other students. This strategy has been shown to be effective in improving the text recall of both high- and low-achieving students, ranging from third grade to college (Brown & Palincsar, 1985; Lysynchuk, Pressley, & Vye, 1990; Palincsar, 1986, 1987), but like the other strategies reviewed, merits additional research, particularly with science texts.

A comparison of SQ4R, MURDER, and reciprocal teaching (Table 1) shows that all three strategies rely on steps that students perform to improve their text comprehension. Some of the steps in the three strategies are similar, whereas others are unique. It is not yet clear which strategy should be used when learning from science text. Perhaps all are equally effective or
perhaps the presence of certain conditions (e.g., cognitive developmental level of the students) would favor one strategy over another. Regardless of the answers to these questions, there are others even more important to answer—more important because they are more fundamental—namely:

1. What are the relative contributions of the component steps in the strategies?
2. What are the cognitive mechanisms by which influential steps have an impact on comprehension?
3. How does the sequence of the steps play a role in comprehension?

Validating the effectiveness of these strategies is important, but it is more important to determine when and how the component steps of these strategies work, particularly when applied to science texts. When acquiring the strategies, it is probably necessary for students to perform the steps in a specified sequence; however, after the strategies are mastered it is reasonable to assume that the students would perform the steps in a recursive, interactive, constructive fashion: one that is consistent with the dynamic nature of proficient reading. These issues represent an important agenda for future research.

**Writing to Learn Science**

Learning to write prepares students for writing to learn. By writing about science topics, students can discover new ideas and clarify their thinking (Butler, 1991; Holliday, 1992; Rivard, 1994; Zinsser, 1988). This goal was expressed well by Karen Kreider, Teacher of the Year at Central High School in Philadelphia:

> My students write to explain, to argue a point of view, to prove a hypothesis. My focus is on their message. Eventually their need to present a clear description or persuasive argument will lead to a concern with the clarity and logic of their message. First and foremost, my students are encouraged to write in order to discover and clarify their ideas. (Woolfolk, 1993, p. 503)

Students who write about scientific topics call upon previously learned science knowledge and science process skills. Writing activities that engage science knowledge and process skills, activate relevant world knowledge, and provide real-world contexts can help to ensure that science learning is constructive rather than rote (Holliday et al., 1994; Keys, 1994).

By bringing writing skills and science process skills concurrently to bear on an activity, students construct new understandings (interpretations) in their working memories (Figure 1). The constructed understandings have the advantage of being meaningful and, therefore, more memorable and applicable. At the same time, these understandings may incorporate reasonable misconceptions about the ideas expressed in the text. As is the case in reading, the formation of reasonable misconceptions is a normal consequence of constructive writing.

Students who are competent writers can retrieve from long-term memory a number of component skills to facilitate expression. These skills include metacognition, idea construction, idea relation, text production, and revision. These skills are consistent with those found in general models of the writing process (e.g., Bereiter & Scardamalia, 1987; Flower, 1989; Flower & Hayes, 1981; Glynn, Britton, Muth, & Dogan, 1982; Glynn, Oaks, Mattocks, & Britton, 1989). Writing has received less attention from researchers than reading and, as a result, fewer component writing skills have been identified in models of writing.

When writing about a scientific topic, students first draw on metacognitive (i.e., strategic
discourse knowledge) skills to formulate audience-specific writing goals and a plan for meeting those goals (Bereiter & Scardamalia, 1987). Students then construct ideas relevant to those goals and retrieve pertinent scientific information from long-term memory, logically relating those ideas to one another. The logical relations in science text often assume the forms identified previously (e.g., exemplification, hierarchical organization, enumeration, causality), and are expressed through content words and relational devices. For example, exemplification is made explicit through words such as “to illustrate,” “for instance,” and “for example.” Organizational relations are more difficult to express in text because the nature of text is linear; however, it is important to express such relations because mental representations of ideas are most effective when hierarchically organized (Kintsch, 1986). Organizational relations are expressed through content words, such as “The primary purpose is...,” and organizational devices, such as levels of headings and paragraphing. Ideally, the implicit hierarchy represented in the written text parallels the explicit one in the student’s mind. By means of the written text, the student endeavors to communicate a mental representation of scientific ideas, which includes not only the ideas but the relations among those ideas (Glynn, Andre, & Britton, 1986; Kintsch, 1986).

Text production involves the formidable skill of communicating a mental representation by means of written sentences. When producing text, students rely upon learned grammar, including vocabulary, syntax (parsing), and sentence mechanics (spelling, punctuation, and word choice). By means of revision, students add, delete, and modify the text to improve it. For the sake of simplicity, these writing skills have been introduced as though they are carried out in a prescribed sequence and, in fact, they are often taught in this sequence. In practice, however, competent writers who have automated these skills to various degrees can juggle several skills concurrently, interactively, and fluidly, thereby reducing the demands imposed on the limited capacities of their working memories and leaving more capacity available for constructing meaning (Glynn et al., 1989). Thus, while producing text, a competent writer also may be revising ideas or relations among ideas. It is important to note that all the writing skills interact with one another in working memory and are coordinated by the writer’s metacognition. The writer who recognizes that the produced text, even after revision, still does not achieve his or her goals, might then revise the plan for meeting those goals or the conceptualization of the audience, or perhaps the goals themselves.

Students’ goals for writing evolve as they develop cognitively over the school years. In terms of Bereiter’s (1980) levels of writing development, students’ writing in the early grades is associative, involving the simple expression of ideas as they come to mind. With maturation and learning, students’ writing evolves and becomes epistemic. The goal of epistemic writing about science is to reflect on, and increase one’s knowledge of science topics.

Writing Activities and Strategies

Writing can play a powerful role in the learning of science. Students with competent writing skills are well on their way to achieving scientific literacy; however, the attainment of literacy also presupposes effective writing activities and strategies.

When students write about their observations, manipulations, and findings, they examine what they have done in greater detail, they organize their thoughts better, and they sharpen their interpretations and arguments. Writing also can help students to diagnose their knowledge gaps and misconceptions. For example, when students respond in writing to real-world questions—Why are there seasons? or How does a computer work?—their responses have learning and assessment advantages that far exceed those of multiple-choice and completion questions. Furthermore, writing enables students to express their intellectual and emotional reactions to
science phenomena (e.g., a sunrise, a snowstorm, or the birth of a farm animal) in a variety of forms (i.e., description, exposition, persuasion, narration, and poetry). Writing activities must be authentic authoring tasks to be effective, that is, they must involve a real audience and they must inform the uninformed, persuade, or call for action. Some authentic authoring tasks for learning science involve asking students to write the following:

1. Explanatory essays in which students describe a complex science concept (e.g., photosynthesis) in depth.
2. Field trip notes in which students record their observations of, and reactions to, flora and fauna.
3. Laboratory logs in which students report their observations, hypotheses, methods, findings, interpretations, and mistakes—particularly mistakes—as these are a normal part of the scientific process.
4. Science journals or diaries in which students describe their participation in science activities, such as fairs and competitions, and reflect on their actions and experiences.
5. Environmental action letters in which students—under the teacher’s guidance—write to politicians, newspaper editors, and companies to promote positive environmental actions.
6. Newspaper accounts in which students write stories on science and technology topics for their school or town newspapers.

The preceding activities, in combination with content-oriented writing strategies, are excellent authentic authoring tasks for learning science. Language educators have developed several strategies for facilitating written expression and avoiding writer's block. Like the reading strategies previously discussed, the writing strategies often contain steps that are taught in a sequence; however, as students attain mastery of the strategy, the steps are performed in a recursive, interactive fashion that is compatible with competent writing.

A widely used writing strategy is “freewriting,” developed by Elbow (1973, 1981). When using this strategy, which is similar to brainstorming, students avoid editing in the initial drafts. Instead, they try to generate as many ideas as possible, paying little or no attention to idea quality, sentence structure, or mechanics. Only in the later drafts, after ideas have been produced and organized, do students attend to sentence structure and mechanics. It has been experimentally demonstrated that the freewriting strategy enhances the idea production of college students (Glynn et al., 1982), probably because it helps students to use their limited-capacity working memories more effectively and reduces their apprehension about producing perfect sentence structure and mechanics.

A variety of content-area writing strategies can be found in the process writing approach of Graves (1983). Many of these self-guiding strategies are developed through teacher modeling and coaching, for example:

1. Write on several topics, not just one, because it's harder to choose one topic than several.
2. Decide what to write first, second, and so on.
3. Put one’s feelings into writing.
4. Write about what you know.
5. Decide why not to write something.

A critical aspect of Graves’s (1983) approach is the writing conference: a short meeting between the teacher and one or more students with the purpose of facilitating the students’ current writing assignments. The conferences are guided by questions that help students to improve their
writing and work through any difficulties they are having. Some examples of these questions are:

1. Opening questions, such as “Where are you at, Jill, in your lab report?”
2. Focusing questions, such as “If you were to include that in your lab report, how would it be helpful to the reader?”
3. Development questions, such as “What changes have you made in your lab report since we last spoke?”
4. Structure questions, such as “Where should you include that new information in your report?”
5. Reflection questions, such as “What do you think is most important in your report?”

Still another content-area writing strategy is the “assisted monologue,” which makes use of “thinking cues” (Bereiter & Scardamalia, 1987, p. 306). In this strategy, students are trained to prompt themselves with directional statements, or thinking cues, when writing. The thinking cues fall into five categories. These five categories and some sample thinking cues are:

1. New idea: “A cause of this effect is. . . .”, and “A practical benefit is. . . .”
2. Improve: “I could add interest by explaining. . . .”, and “To put it more simply. . . .”
3. Elaborate: “An explanation would be. . . .”, and “An example of this is. . . .”
4. Goals: “My purpose is. . . .”, and “This paper is about. . . .”
5. Putting it together: “I can tie this together by. . . .”, and “I can show a relationship by. . . .”

Bereiter and Scardamalia demonstrated the effectiveness of the “assisted monologue” strategy with sixth graders who were asked to write factual exposition essays. This strategy, like the freewriting strategy and the various strategies of Graves (1983), would likely prove quite effective in helping students to write about science topics.

As was the case with the reading strategies discussed, the research agenda here should extend beyond simply validating the effectiveness of these strategies when writing about science topics. A more important question is: What are the relative contributions of various steps or components in the strategies? It is of primary importance for researchers to identify how these steps and components influence writing and how students can be supported most effectively when writing in the area of science.

Integrating Reading, Writing, and Science

What needs to be developed now are strategies that integrate both reading and writing in the learning of science. By integrating reading and writing activities, a complementary scientific literacy environment can be established that is mutually supportive (Baker & Saul, 1994). In such an environment, students read about what they write and write about what they read. The reading and writing strategies previously discussed can provide a starting point for the creation of new integrated strategies.

Science-Learning Strategies

Another starting point for the creation of integrated strategies are those already popular with science educators, such as concept mapping (Novak, 1990). Science educators support students’ constructive, relational learning by means of concept mapping, a strategy for constructing a
representation of the elements of information in a conceptual network and the relations among those elements. The products of this strategy are concept maps (e.g., Fellows, 1994; Novak, 1990). Science teachers and textbook authors use concept maps to plan lessons and introduce those lessons to students. Even more important, teachers can model the process of concept mapping for students so that students can learn to construct their own concept maps. The concept-mapping strategy can be integrated with reading and writing activities to help students learn science more effectively (Fellows, 1994). For example, concept mapping, in combination with the writing strategy of freewriting, can provide a supportive framework for idea generation and organization. After the concept map is generated, it can then be translated into sentence structure. Incorporating concept mapping and other strategies (e.g., Vee-diagrams and concept circle diagrams in Wandersee, 1990), currently used by science educators into integrated reading and writing activities, is yet another agenda for research.

**Intelligent Tutoring Systems**

Perhaps the largest agenda for research and the one with the greatest potential for effectively integrating reading, writing, and learning science involves intelligent tutoring systems (ITSs). ITSs support students' learning of concepts in a discipline. In the area of science, for example, there is ThinkerTools, an ITS that teaches sixth graders the basic principles of Newtonian mechanics (White, 1993). An ITS consists of various modules, one of which is the learning environment defined as “that part of the system specifying or supporting the activities that the student does and the methods available to the student to do those activities” (Burton, 1988, p. 109). These activities should include reading and writing, if the goal is to construct a learning environment that supports scientific literacy.

In order to design ITS learning environments that integrate reading, writing, and science learning, researchers must determine exactly what expert human teachers actually do. In doing this, researchers will rely increasingly on qualitative research methods, such as task analysis, systematic interviewing, introspection (thinking out loud), and the analysis of written protocols (Muth, Glynn, Britton, & Graves, 1988; Wiggs & Perez, 1988).

**Conclusions**

In addition to the textbook-driven versus teacher-driven distinction made previously, curricula can be categorized in at least three other ways: integrated, interrelated, and isolated (Goetz, Alexander, & Ash, 1992). In an integrated curriculum, content is organized around topical themes to which several content and skill areas are connected without one area dominating over the other. The integrated curriculum is often found in the elementary grades and increasingly in the middle grades. In the interrelated curriculum, the content and skill areas are taught separately but are cross-referenced for purposes of illustration, elaboration, or enrichment. The boundaries between areas are softened and the connections emphasized. And finally, in the isolated curriculum, content areas and basic skills are taught independently of each other. This is often the case in high schools where the major science disciplines are separated into yearlong courses: earth and space science in 9th grade, biology in 10th, chemistry in 11th, and physics in 12th (for those few students still in the “pipeline”). In high school, writing (composition) is usually taught isolated from science; reading, if it is taught, is remedial in nature and also isolated.

It could be argued that reading and writing to learn science takes place most effectively in an integrated curriculum (Gaskins et al., 1994). Alternatively, it could be argued that the kind of
curriculum is irrelevant: What is important is that the teachers are knowledgeable and empowered. Teachers are empowered when they are not straightjacketed by textbook programs, instructional methods, and assessment approaches imposed on them in a top-down fashion. Teachers are knowledgeable when their knowledge extends beyond science to encompass knowledge about how to integrate reading and writing activities in the learning of science. Yore (1991) surveyed 215 high school science teachers and found that they placed high value on the role of reading in learning science. The teachers were willing to accept responsibility for teaching content-reading skills and had good intuitive understanding of the reading process. The teachers indicated, however, that they were not familiar with well-formulated strategies to guide their teaching practices. Shymansky, Yore, and Good (1991) found similar results with elementary school teachers.

What steps should be taken to familiarize science teachers with reading and writing strategies? One step is to revise teacher pre-service and in-service programs to include an emphasis on reading and writing to learn science. Another is to work with publishers to produce flexible guides for using reading and writing activities in the learning of science. Commendably, some publishers have begun doing this. Heath, for example, published the well-received *Writer's Guide to Life Sciences* (Biddle & Bean, 1987) as a reference for both teachers and students. Guides of this kind will help science teachers and students to guard against reading and writing becoming rote, as when a laboratory report is read or written as though it were a recipe in a cookbook.

Integrated reading and writing activities can play a vital role in achieving a minds-on emphasis in the learning of science. Reading and writing activities can support active, constructive learning, inquiry, and problem solving. Reading and writing activities can help students to cover science content in greater depth, focusing on related ideas and themes. Through reading and writing, students can build upon their prior learning and make real-world connections. In short, the skills of reading and writing can serve as dynamic vehicles for learning science meaningfully.

To help students achieve scientific literacy, science teachers should ensure that each school's curriculum includes integrated reading and writing activities. Educational researchers can play a vital role in this process by providing teachers, teacher educators, administrators, and policy makers with information about the creation of a curriculum that supports science literacy. Educational researchers can build upon the craft knowledge of teachers and develop state-of-the-art strategies that capitalize on rapidly evolving ITS technology. In this way, a scientifically literate curriculum—one in which students read and write to learn science—can be achieved.

The work reported herein was prepared with partial support from the National Reading Research Center of the University of Georgia and University of Maryland. It was supported under the Educational Research and Development Centers Program (PR/AWARD No. 117A20007) and administered by the Office of Educational Research and Improvement, U.S. Department of Education. The findings and opinions expressed here do not necessarily reflect the position or policies of the National Reading Research Center, the Office of Educational Research and Improvement, or the U.S. Department of Education.
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Manuscript accepted December 23, 1993.