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Examining the literacy component of science literacy: 25 years of language arts and science research

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This review, written to celebrate the 25th anniversary of the *International Journal of Science Education*, revealed a period of changes in the theoretical views of the language arts, the perceived roles of language in science education, and the research approaches used to investigate oral and written language in science, science teaching, and learning. The early years were dominated by behavioralist and logico-mathematical interpretations of human learning and by reductionist research approaches, while the later years reflected an applied cognitive science and constructivist interpretations of learning and a wider array of research approaches that recognizes the holistic nature of teaching and learning. The early years focus on coding oral language into categories reflecting source of speech, functional purpose, level of question and response, reading research focused on the readability of textbooks using formulae and the reader's decoding skills, and writing research was not well documented since the advocates for writing in service of learning were grass roots practitioners and many science teachers were using writing as an evaluation technique. The advent of applied cognitive science and the constructivist perspectives ushered in interactive–constructive models of discourse, reading and writing that more clearly revealed the role of language in science and in science teaching and learning. A review of recent research revealed that the quantity and quality of oral interactions were low and unfocused in science classrooms; reading has expanded to consider comprehension strategies, metacognition, sources other than textbooks, and the design of inquiry environments for classrooms; and writing-to-learn science has focused on sequential writing tasks requiring transformation of ideas to enhance science learning. Several promising trends and future research directions flow from the synthesis of this 25-year period of examining the literacy component of science literacy – among them are critical listening and reading of various sources, multi-media presentations and representations, effective debate and argument, quality explanation and the role of information and communication technologies/environments.

Introduction

The period 1978–2003 represents 25 years of exciting explorations into relationships between language and science learning based on the convergence of perspectives and models now known as the applied cognitive sciences, which was and could just as well have been called the learning sciences. The work on oral and written language arts in science education prior to this period was dominated by either a behaviorist or a logico-mathematical perspective in which speaking, listening, reading, and writing were ignored or portrayed as unidirectional processes: speaker to listener, text to reader, or memory to text. The advent of the cognitive sciences and the recognition of the limited perspectives of stimulus–response–reinforcement, the under-emphasis of social transmission, and the

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understated role of language in these perspectives did much to advance an understanding of the literacy component in science literacy (Mattheissen, 1998). Since the late 1970s, more balanced perspectives of science learning and the language arts have led many language and science education researchers to seek compatible models of learning involving sensory experiences, oral discourse, textual materials, and writing about experiences that are situated in a sociocultural context (Holliday, Yore, & Alvermann, 1994). Osborne and Wittrock stated:

> To comprehend what we are taught verbally, or what we read, or what we find out by watching a demonstration or doing an experiment, we must invent a model or explanation for it that organizes the information selected from the experience in a way that makes sense to us, that fits our logic or real world experiences, or both. (1983, p. 493)

The explorations into the connections among mental models, language, and science learning have been influenced by the history and philosophy of disciplines, the insights into human cognition and metacognition, and the application of information and communication technologies (ICT) in literacy education and science education communities. The results of the academic research and the grass roots development activities have, in turn, influenced educational reforms, teacher education, curricula, instructional resources, and classroom practices. In this article, we will outline the historical foundations for the language-science claims, some current critical results and promising endeavors, and future directions.

Science literacy

The science education reforms in Australia (Curriculum Corporation, 1994), Canada (Council of Ministers of Education, Canada, 1997), New Zealand (Ministry of Education, 1993), the UK (Department of Education, 1995), and the US (National Research Council, 1996) promote a standards-based definition of science literacy for all people as abilities and habits-of-mind required to construct understandings of science, to apply these big ideas to realistic problems and issues involving science, technology, society and the environment, and to inform and persuade other people to take action based on these science ideas (Hand, Prain, & Yore, 2001). But these documents are relatively silent on the specific roles of reading and writing in science education. The English language arts reforms in these countries promote language literacy that stresses knowledge about the main ideas in language arts and encourage crossing borders into other discourse communities. But again, these documents say little about the specific application of the language arts in science and in science education.

A recent article by Norris and Phillips (2003), however, illustrates how these reform movements may relate. They established a compelling claim about science literacy based on a classic analysis of language and philosophy in which science literacy embodies two essential senses: the fundamental sense, and the derived sense. The fundamental sense involves the traditions of being a learned person and the abilities to speak, read, and write in and about science. The derived sense involves knowing the corpus of knowledge in science. The fundamental sense subsumes the abilities, emotional dispositions, and communications of the current standards-based definition of science literacy, while the derived sense subsumes the understanding and application of the big ideas of science in the standards-based definition of science literacy including the unifying concepts of science, the nature of science, the relationships among science, technology, society and environment, the procedures of science, and the social relevance of science.

Language is an integral part of science and science literacy – language is a means to doing science and to constructing science understandings; language is also an end in that it is used to communicate about inquiries, procedures, and science understandings to other people so that they can make informed decisions and take informed actions. The over-emphasis on formulae in school science suggests to most people that mathematics is the language of science; but when the vision is expanded to include authentic science in research, applied and public awareness settings, it becomes apparent that mathematics is not the exclusive language system across all science domains. Rather, spoken and written language is the symbol system most often used by scientists to construct, describe, and present science claims and arguments.

Language in science

The international calls for language literacy and science literacy that stress communications with various audiences and language communities, and promote involvement in the public debate about scientific, technological, societal, and environmental issues have put more attention on speaking, listening, reading, and writing in science classrooms and on how an increased variety of language tasks might increase both science understanding and language arts performance (Hand *et al.*, 2001).

> To do science, to talk science, to read and write science it is necessary to juggle and combine in various canonical ways verbal discourse, mathematical expression, graphical–visual representation, and motor operations in the world. (Lemke, 1998, p. 87)

Oral and written science communications are multi-dimensional involving language, physical gestures, mathematical symbols, and visual adjuncts. While there has been some recognition given to the value of using discussion, argumentation, reading, and writing to help students construct understandings of science (Rowell, 1997; Wellington & Osborne, 2001; Yore & Shymansky, 1985), there exists limited literature on how the nature of science influences the characteristics and content of oral and written discourse, what language processes scientists use to construct science and to inform different audiences of their work, and how these processes can be applied in science classrooms to promote science learning.

Nature of science

Scientists use unique patterns of argumentation that attempt to establish clear connections among claims, warrants, and evidence (Holland, Holyoak, Nisbett, & Thagard, 1986; Kuhn, 1993). The specific nature of science from a philosophical perspective has been contested in recent years, with cultural relativists refusing to accept science's traditional claims to durable standards of truth, objectivity, and reputable method (Norris, 1997) and the multiculturalists promoting multiple sciences (Stanley & Brickhouse, 2001). However, Lederman (2001) cautioned that some people misrepresent the magnitude and focus of the disagreement about the nature of science, and noted there is reasonable agreement about the general tentative, procedural, and declarative aspects of science. Cobern and Loving outlined the critical attributes of science:

> Science is a naturalistic, material exploratory system used to account for natural phenomena that ideally must be objectively and empirically testable. (2001, p. 58)

> The Standard Account of science is grounded in metaphysical commitments about the way the world 'really is'. (2001. p. 60)

These fundamental components suggest that science is people's attempt to systematically search out, describe, and explain generalizable patterns of events in the natural world, and that the explanations stress natural physical causalities, not supernatural or spiritual causes (Good, Shymansky, & Yore, 1999).

> Explanations about the natural world based on myths, personal beliefs, religious values, mystical inspiration, superstition, or authority may be personally useful and socially relevant, but they are not science (National Research Council, 1996, p. 201).

Ontological and epistemological considerations

A big idea promoted in the current definition of science literacy is an understanding of the competing views of science – traditional, contemporary, and postmodern (Hand *et al.*, 2001; Nussbaum, 1989). The science education reforms in the US promote a contemporary interpretation of the nature of science. In this view, science is the search to describe reality that is becoming more and more accurate, and multiple interpretations of an experience or data set are likely, but that these interpretations must be submitted to public judgment using the available evidence extracted from nature and the established science. This naïve realist, evaluativist interpretation of science is viewed as inquiry; and the resulting science knowledge claims are viewed as speculative, temporary, and rational. Utilizing this or a similar view of science, Hurd (1998) suggested that a scientifically literate person is one who:

1. distinguishes experts from the uninformed, theory from dogma, data from myth and folklore, science from pseudo-science, evidence from propaganda, facts from fiction, sense from nonsense, and knowledge from opinion;
2. recognizes the cumulative, tentative, and skeptical nature of science; the limitations of scientific inquiry and causal explanations; the need for sufficient evidence and established knowledge to support or reject claims; the environmental, social, political and economic impact of science and technology; and the influence society has on science and technology; and
3. knows how to analyze and process data, that some science-related problems in a social and personal context have more than one accepted answer, and that social and personal problems are multidisciplinary having political, judicial, ethical, and moral dimensions.

Science distinguishes itself from other ways of knowing and from other bodies of knowledge through the use of empirical standards, logical arguments, plausible reasoning (abduction, induction, deduction, and hypothetico-deduction), and skepticism to generate the best temporal explanations possible about reality (Hofer & Pintrich, 1997). Scientific explanations must be consistent with observational evidence about nature, emphasize physical causality, and facilitate accurate predictions, when appropriate, about the systems studied. Evaluations of knowledge claims should be logical, respect the rules of evidence, be open to criticism, report methods and procedures, and make knowledge public (National Research Council, 1996).

Scientists as language users

Oral and written communication and the processes of speaking, listening, writing, and reading are highly valued within the scientific community; scientists who communicate well are successful in gaining support from members of their own communities, funding agencies, and the wider society. Several researchers have attempted to investigate specific language, purposes, and approaches scientists use to obtain funding, do science, report results, and influence public policy about their work and how it relates to current science–technology–society–environment (STSE) issues. Collectively, the studies revealed common tasks, strategies, and processes across groups of scientists and research teams including aspects of language uses, reading habits, and planning, drafting, and revising reports (Bazerman, 1988; Chaopricha, 1997; Dunbar, 2000; Florence, 2001; Yore, Hand, & Prain, 2002).

Necessary role of oral language in science

Professional conversations for scientists involve a full range of verbal tasks: talking to other scientists face to face or at a distance, speaking to small and large groups of students and scientists, presenting and debating ideas on radio and television, and leaving voice-mail messages to staff and colleagues (Yore, Florence, Pearson, & Weaver, 2002). These unidirectional and interactive communications require scientists to establish purpose, consider audience, mentally compose understandable messages, deliver the message in an effective and persuasive manner, and listen to the responses.

The language that scientists use varies with the purpose and setting. When speaking to laypeople, scientists may use an informal style containing minimum terminology, frequent non-verbal gestures to augment spoken words, and appropriate metaphors and analogies to connect to their audience's experiences and knowledge. Likewise, a scientist in an instructional setting uses somewhat more formal language and technical vocabulary to match the students' academic level – a first-year introductory course for non-majors approximates the style and terminology for lay audiences, while an advanced graduate course approximates the style and technical vocabulary of an academic conference presentation.

Each of these communications is intended to convey a message without distorting the science or over-stating the certainty of their claims. Scientists who wish to communicate, inform, and persuade listeners use the linguistic tools necessary to bridge the gap between speaker and listener, and oral citations of other scientists' work to connect their message to established ideas or canonical science. The effectiveness of these communications depends on the speaker's ability, the listener's background, and the complexity and abstractness of the target ideas. Not all communications are effective, as illustrated when an evolutionary biologist debates a religious creationist. In this situation, the terminology of the two communities is different (in the former 'theory' is an umbrella concept that integrates well-established science ideas, whereas in the latter 'theory' is an unproven speculation); unless there is an attempt to agree to use a shared vocabulary, communications will often fail and result in a shouting match in which speakers talk past their audience rather than talking with their audience (Good *et al.*, 1999).

In popular culture, scientists are frequently portrayed as 'good' talkers but 'bad' listeners. This stereotype is not true! Feynman (1985) described how impressive the researchers working on the atomic bomb were as speakers and listeners. He described the oral presentations and discussions that occurred during the early years of nuclear research at Princeton, Cornell, and Los Alamos. These scientists put together cogent arguments about abstract ideas without the aid of graphics and equations, and without producing less than accurate descriptions of reality. Elsewhere, scientists in research team meetings and conferences listen intently to assess the significance of the presenters' claims, the credibility of their data, the supportiveness of their evidence, and the augmentation of their citations in an attempt to evaluate the strength of the argument presented (Florence, 2001).

Essential role of print-based language in science

It is unlikely that contemporary science would have developed as it has in a strictly oral culture or discourse community (Norris & Phillips, 2003). 'Symbols mediate not only communications but also thought itself'(Howard & Barton, 1986, p. 21). Locke believed that language does not simply describe

> what the scientist does but it actually helps determine it. The relationship of the scientific paradigm and its language is a reciprocal one: language shapes the paradigm, and the paradigm shapes the language. (1992, p. 33)

Chaopricha stated:

> Any claim to the priority of discovery requires suitable, trustworthy, and persuasive methods for communicating the work that constitutes the claim to priority. Verbal or informal communication is not sufficient. (1997, p. 12)

The attention to pattern, sequence, and detail, and the connectedness of claims, evidence, and warrants required by science are nearly impossible in oral discourse. The real-time speed of oral conversation in many cultures minimizes the opportunity to reflect. The short wait-time between question and response when two people are speaking promotes impulsive instead of reflective conversations.

Language as technology needs to be considered when addressing the connections between language literacy and science literacy (Martin, 1993). People use language as a tool to direct intellectual power to problems much the same way that a craftsperson selects a tool from a toolkit to direct physical power to problems (Greenfield, 1991). The structures of problem–solution, cause–effect, and explanation forms of scientific text (genre) are linguistic devices that promote functional and connected discourse in which two or more ideas are related to form propositions and knowledge claims. Scientists use strategies like nominalization, analogies, logical connectives, and intertexuality to justify their procedures and to construct knowledge claims. Intertextuality – the citation of well-regarded scientists' work – is the most common technique of 'scholarly bricklaying' used to demonstrate how current methods and knowledge claims connect to established research procedures and canonical knowledge (Chaopricha, 1997, p. 16).

Locke (1992) provided several interpretations of science as writing that address the current debate on the nature of science and science literacy – science writing as representation, as rhetoric, and as reality. Changes in the ontological (realist, naïve realist, idealist) assumptions and epistemological (absolutist, evaluativist, relativist) beliefs about science suggest parallel changes in the interpretation of the role of language in science from traditionalist–representational to non-traditionalist–constitutive. The traditional–representational interpretation of language in science involves finding truth, temporary truth, or multiple truths and describing the truth verbatim. Traditionalist (realist, absolutist) scientists see two cultures, two languages, delineating:

> scientific language as essentially representational and devoid of those other qualities – expressivity, affectivity, artfulness, social artifactuality, textual constitutivity. (Locke, 1992, p. 18)

These scientists perceive written text as a transcription of what has been done, independent and following from the inquiry, serving 'no purpose other than to transmit clearly whatever view [that] lies behind it' (Locke, 1992, p. 16). On the other hand, non-traditional postmodern (idealist, relativist) scientists view written science text as a social artifact of the culture constituting reality and carrying implicit messages of power, class, gender, race, and ethnicity. These scientists 'insist that scientific knowledge is made, not discovered' (Locke, 1992, p. 12) and that, although one interpretation may appear true, there may be others, since it is impossible to ever know the truth about the world. These two philosophical camps find little common ground in the role and value of language. The predominant middle-of-the-road scientists hold contemporary views of science (naive realist, evaluativist) and perceive language as an integral part of science, integrated with inquiry, and a critical part of making sense of the inquiry. These scientists view writing as a constitutive process in which the reflection on text allows them to evaluate the quality of their evidence and argument and to assess the need to return to further inquiries (Yore, Hand, & Florence, 2001). Science discourse is rhetoric in that it attempts to inform and persuade other scientists about the validity of the scientific knowledge claims and the value of proposed inquiries.

There are many important scientific journals, and the types of writing within the scientific community are several (Goldman & Bisanz, 2002). However, scientists generally read the same journals they write for, and the peer-reviewed journal article is the predominant genre read (Yore *et al.*, 2001). Research reports have a structure well known in the scientific community, beginning with the 'Introduction' (where the history of knowledge claims in the literature is developed and the focus of the paper is established), the 'Experiment' (composed of method and results, which are the meat of the paper), and the 'Discussion' (where major findings are highlighted, arguments are made about how they extend knowledge in the field, and results are hedged to reflect the uncertainty). More detailed discussion can be found elsewhere (Goldman & Bisanz, 2002). Such reports are read before, during, and after conducting experiments in scientists' research areas (Yore *et al.*, 2002). Reading is done with pencil in hand, jotting down interesting ideas, checking calculations, and often writing margin notes (Mallow, 1991). In their fields of expertise, scientists' tend to read to update their knowledge by identifying what is new in the report, looking at the Results and Discussion sections first, rather than reading the report sequentially. Less attention is paid to Methods on an initial reading, assuming that reports that have passed through the peer-review process are likely to be sound (Bazerman, 1988; Berkenkotter & Huckin, 1995). When reading outside their field, scientists indicate that they read for general interest and begin with the Introduction (Berkenkotter & Huckin, 1995). When serving as reviewers for peer-reviewed journals, scientists serve as gatekeepers, attending to all sections of the paper. Reading with this purpose, they set high standards for the quality of the science reported, coherence, external validity, importance, and newsworthiness of the writing (Bazerman, 1988; Berkenkotter & Huckin, 1995). When scientists encounter comprehension difficulties, they make cost/benefit judgments – judgments such as the trustworthiness of the author, how reasonable the approach was, and the validity of the knowledge claims determined whether an article with writing problems was worth their time. In summary, scientists are pragmatic readers; their purpose for reading, prior knowledge, and evaluation criteria all influence their reading strategies.

Research on language arts and science learning

This part of the literature review on the language arts and science learning concentrates on the first 15 years that coincided with publication of the *International Journal of Science Education* (1978–1993) to provide a historical perspective, leaving the last 10 years (1994–2003) to be considered as current results and promising endeavors in the next part of this article. As indicated previously, the 1978–1993 period represents the transition from the reductionist influences of behaviorism and logico-mathematical influences on the study of cognitive development to the linguistic, philosophical, psychological, sociocultural, and contextual influences of applied cognitive science.

Oral language and science education

Historically, verbal interaction in the form of teacher questioning and student responding has been a central part of classroom research. Interaction analysis research used well-developed coding systems and sequential responses in a fixed time interval to document, categorize, map, and analyze oral discourse in classrooms (Flanders, 1964). Many of these techniques assumed traditional teacher-directed verbal patterns of initiation, response, and follow-up, predetermined levels of questions and responses, or sources and functions of speech, and were not well suited for laboratory work, unstructured discussions in small groups, and discovery-based science instruction. With the availability of microelectronic technology and computer analysis, several video, audio, and real-time analysis systems were developed. The macro-analysis system was a much more open and flexible approach that allowed investigators to document and explore laboratory discussions and unscripted instructional approaches (Shymansky, 1978).

Teacher questioning was the central focus of many early studies in which question level, wait-time, and questioning strategies were investigated (Wise & Okey, 1983). In traditional teacher-directed classrooms, questions were used to manage and evaluate students; while in inquiry-oriented classrooms, questions were used to facilitate and scaffold student learning. Rowe (1974) and Tobin (1980) found that the quality and length of student responses increased if the teacher asked the question, paused for 3–5 seconds, and then called on a specific respondent.

Other research found that higher-level questions stimulated improved achievement, and that prompting, probing, chaining, and redirecting student-initiated questions enhanced the quality of classroom discourse and student cognitive learning, critical thinking, and creativity (Wise & Okey, 1983).

The advent of constructivist learning models and the search to describe and explain the classroom practices associated with various constructivist teaching approaches moved verbal discourse onto center stage of science education research. Many researchers used Piagetian-type interviews to access and assess people's understanding of science and think-aloud protocols to document people's mental processes (Driver, Guesne, & Tiberghien, 1985). Lemke (1990) forged a new perspective on oral discourse analysis by considering the context and global sense of the interactions. He explored the oral discourse that occurred in laboratories, classroom instruction and small group discussions, and helped science educators and teachers view talk and action as central social processes in science learning. Student discussions and interactions in small and large groups were generally viewed as a positive influence on science achievement and learning skill development at all levels of education (Gayford, 1993; Kempa & Ayob, 1991; Robinson & Niaz, 1991). The research results were somewhat mixed in these early studies, finding in unstructured laboratory settings that much of the verbal interactions were lower level with only a minority of students demonstrating the epistemic vocabulary and language patterns found in authentic science inquiries. Students infrequently developed the language of scientific argumentation or the patterns of argument that stress claims, evidence, and established science concepts and frequently were side tracked from the central learning tasks by social conversation. There was some consideration of instructional approaches that attempted to structure tasks and related verbal discourse in an attempt to enhance students' scientific meta-language, argumentation, and understanding using controversy and classical debate in a STSE context (Gayford, 1993; Johnson & Johnson, 1985). The STSE context appeared to provide a rich, authentic problem space with legitimate alternative interpretations and solutions worthy of deliberation and the evaluation, revision and replay of the argument emphasized self-regulation (metacognition) and the norms of claims, evidence, warrants, counter claims, and rebuttals central to science.

Written language and science education

Science reading, science writing, and writing-to-learn science were influenced by several models and grass-root movements (Rivard, 1994; Rowell, 1997; Yore & Shymansky, 1985). Reading and writing research in science education was sparse during the early years of the *International Journal of Science Education* because of the overwhelming desire to promote hands-on activities and to move away from science textbooks and worksheets. But, the meta-analyses of the 1980s suggested that hands-on activities without some form of minds-on supplemental activities were not as effective as promoted (Shymansky, Kyle, & Alport, 1983; Willett, Yamashita, & Anderson, 1983; Wise & Okey, 1983).

Science reading. Many studies of science reading in the early part of the 1978–1993 period emphasized the issues of textbooks' content and style, students' reading skills, and teachers' use of textbooks as if they were independent dimensions of reading. Readability formulae, reading skills tests, text analysis, page format, and end-of-text questions dominated the inquiries (Dreyfus, 1992; Shymansky & Yore, 1979; Williams & Yore, 1985). A parallel set of inquiries attempted to document teachers' uses of textbooks and their attitudes toward and knowledge about science reading in elementary and secondary science classrooms (DiGisi & Willett, 1995; Gottfried & Kyle, 1992; Shymansky, Yore, & Good, 1991; Yore, 1991). These studies of textbooks, skills, uses, attitudes, and knowledge revealed that:

- decisions to buy a science textbook influenced the delivered curriculum and instruction;
- science textbooks were above grade-level reading and readability varied across disciplinary topics and chapters;
- the use of four-color and visual adjuncts in the textbook did not necessarily improve comprehension for all reading abilities;
- the pattern of arguments and explanations were relatively unchanged over a 70-year period;
- there was little evidence of explicit science reading comprehension instruction in elementary and secondary science classrooms; and
- teachers' attitudes toward science reading were reasonably positive and their knowledge about science reading indicated that reading was more than simply skills and textual material.

Fortunately during this period of time, the interpretation of reading evolved from text-driven models, to reader-driven models, and, finally, to the interactive reader and text models. The changing interpretations reflected the rejection of reading as taking meaning from text and reading as readers creating meaning exclusively to the acceptance that readers make sense of text.

> No longer do we think of reading as a one-way street from writer to reader, with the reader's task being to render literal interpretation of text. (Samuels, 1983, p. 260)

Science reading can be conceptualized as an interaction between what is known, concurrent sensory experience, and information accessed from print in a specific sociocultural context that is directed at constructing meaning (Ruddell & Unrau, 1994). Readers must interactively process information by instantly switching back and forth between selective perceptions of text-based information and concurrent experience, on the one hand, and by comparing the information and experience with their personal world-view recollections in short-term memory, on the other. Readers construct understanding in short-term memory by extracting information from the text-based situation and concurrent experience – called bottom-up processing – by retrieving information from their long-term memory and deciding what should be considered in a specific context – called top-down processing – while monitoring, strategically planning, and regulating the global meaning-making process – metacognition (Rivard & Yore, 1992). Valencia and Pearson stated that the interactive–constructive view of reading:

> emphasizes the active role of readers as they use print clues to 'construct' a model of the text's meaning. It de-emphasizes the notion that progress toward expert reading is the aggregation of component skills. Instead, it suggests that at all levels of sophistication, from kindergarten to research scientist, readers use available resources (e.g., text, prior knowledge, environmental clues, and potential helpers) to make sense of text. (1987, p. 727)

Flood stated:

> Readers approach texts as blueprints, as guides that enable them to construct meaning. Texts establish broad limits of possible meanings, but they do not specify a single meaning. Readers (not texts) create meaning through negotiations with authors. (1986, p. 784)

van Dijk and Kintsch (1983) described these real-time negotiations as a conflict resolution process that progressively solves meaning problems involving text-based interpretations extracted from print, the reader's episodic memory and semantic memory, and the situation's sociocultural context. Episodic memory involves stored recollections about the conceptual topic; semantic memory involves the reader's worldview of language structures, linguistic rules, science text, and the scientific enterprise; while the sociocultural context involves practices, standards, beliefs, and expectations that set boundaries for acceptable resolutions. This conflict resolution interpretation de-emphasizes the aggregation of individual skills, leading to expert reading status while emphasizing the importance of prior knowledge and the metacognition of the process. Metacognition is composed of two clusters: metacognitive awareness, and executive control.

Constructivist perspectives in science education stimulated reading researchers and science education researchers to re-visit their earlier assumptions and beliefs about the role of textual material and reading in science instruction at elementary, secondary, and post-secondary levels. This new interpretation of science reading re-directed much of the science reading research toward the interactions between text and reader, readers' metacognition, how teachers integrated textual materials, talk and inquiry activities, and how explicit instruction might improve science reading strategies, metacognitive awareness, and executive control (Guzzetti, Snyder, Glass, & Gamas, 1993; Rivard & Yore, 1992).

Science writing and writing-to-learn science. Writing across the curriculum has been characterized by a series of practitioner-led efforts in Australia, Canada, the UK, and the US, leaving numerous effective programs undocumented. Rivard (1994) reviewed and summarized the writing-to-learn studies reported in the research journals, but limited writing-to-learn science studies were found. The emphasis in the 1978–1993 period was on narrative writing; when writing was used in science instruction, it fulfilled an evaluation function – to assess what students know about a specific topic. Langer and Applebee (1987) found that most student writing was short, informational passages and intended for the teacher as audience; and there were differences in the way social studies and science teachers used writing. Social studies teachers used writing tasks to elaborate and enrich classroom learning, while science teachers used writing for evaluation.

The dominant view of writing was a knowledge-telling model in which the writer converted recollections, mental models, and conceptions of science ideas into print representation unaltered. Teachers interpreted this model as a way to evaluate students' understanding using essays and short-answer questions. Students used the knowledge-telling model mechanically to select a topic, recall understanding, draft a product, proofread the draft, and produce a final copy. Frequently, the writing process was linear, devoid of any sociocultural interactions, and emphasized the mechanics of the language.

An apparent weakness of the knowledge-telling model of science writing is that this model does not accurately reflect the transformational and recursive nature of authentic science writing, the unique characteristics of the science domains, the pedagogical purposes for writing in science, the variety of potential writing tasks in science, and the understandings of the participants – teachers and students. Holliday *et al.* stated:

> Writing, like interactive-constructive reading, depends upon the writer's prior domain and strategic knowledge, purpose, and interest. Bereiter and Scardamalia (1987) described the interactive and constructive processes involved in the knowledge-transforming model of writing that parallels the generative model of science learning in that it involves long-term memory, working memory, and sensory-motor activity. The knowledge-transforming model appears to be far more interactive and recursive than linear. The tasks of goal-setting and text production do not fully reveal the complex cognitive, metacognitive, and memory factors involved in the retrieval of conceptual and discourse knowledge from long-term memory and the executive control, strategic planning, and construction taking place in short-term memory. (1994, pp. 885–886)

The knowledge-transforming model encouraged science teachers to have students spend more time setting purpose, accessing content knowledge, specifying audience, thinking, negotiating, strategic planning, reacting, reflecting, and revising. From this perspective, explicit instruction embedded in the authentic science inquiry designed to clarify language as a symbol system and tool, the process of writing, scientific genre, the responsibilities to the audience, the nature of science language, the patterns of argument, and metacognitive awareness and executive control of writing and writing strategies should be an integral part of science courses (Ferrari, Bouffard, & Rainville, 1998; Sawyer, Graham, & Harris, 1992).

Effective writing-to-learn science programs need to provide explicit instruction and writing tasks that consider the full range of genre (the specific function–form relationships of science writing), including narrative, description, explanation, instruction, and argumentation (Gallagher, Knapp, & Noble, 1993). Narrative involves the temporal, sequenced discourse found in diaries, journals, learning logs, and conversations. Description involves personal, common-sense and technical descriptions, informational and scientific reports, and definitions. Explanation involves sequencing events in cause–effect relationships. Instruction involves ordering a sequence of procedures to specify directions, such as a manual, experiment or recipe, and can effectively utilize a series of steps in which the sequence is established by tested science and safety. Argumentation involves logical ordering of propositions to persuade someone in an essay, discussion, debate, report, or review. Each genre is flexible, and the writer must control the form to address the function or purpose. Analysis of effective writing illustrates that no lengthy piece of writing uses a single genre, but rather it includes embedded passages with unique form and function (Yore, 2000).

Connolly (1989) suggested that this new writing-to-learn rhetoric was compatible with constructivist perspectives of science learning. He emphasized:

> Writing-to-learn is not, most importantly, about 'grammar across the curriculum' nor about 'making spelling count' in the biology paper. It is not a program to reinforce Standard English usage in all classes. Nor is it about . . . mastering the formal conventions of scientific, social scientific, or business writing. It is about the value of writing 'to enable the discovery of knowledge.' (Connolly, 1989, p. 5)

However, writing-to-learn science tasks also provide authentic opportunities to develop vocabulary, grammar, spelling, punctuation, patterns of argumentation, and technical writing utilized in the science and technology professions. Howard and Barton stated that the

> idea is to learn to think in writing primarily for your own edification and then the eyes of others. This approach will enable you to use writing to become more intelligent to yourself – to find your meaning – as well as to communicate effectively with others. (1986, p. 14)

Tchudi and Huerta (1983) provided the following guidelines for developing writing-to-learn tasks in science:

- keep science content central in the writing process;
- help students structure and synthesize their knowledge;
- provide a real audience for student writers;
- spend time pre-writing, collecting information from various sources, sharpening focus, and strategic planning;
- provide on-going teacher support, guidance, and explicit instruction;
- encourage revisions and re-drafts based on supportive criticism; and
- clarify the differences between revising and editing.

Universities and colleges were among the earliest institutions to incorporate writing into their educational goals, curriculum, and requirements. The University of Hawaii adopted a writing-intensive course requirement for A.A., B.A., and B.S. degrees in 1987 (Chinn, Hussey, Bayer, & Hilgers, 1993). All students must complete five writing-intensive courses in their major area. Writing-intensive courses require that:

- writing be used to promote learning;
- student and professor interact during the writing process;
- writing play a major role in course grades;
- students produce a minimum of 4000 words or 16 pages of text; and
- class enrollment be limited to 20 students.

Writing in university and college science courses to promote epistemic insights, thinking, and conceptual understanding requires utilization of science-appropriate genre (Mullins, 1989). Moore (1993) found that college students' science achievement improved if writing was coupled with explicit writing instruction and embedded in actual science courses. Liss and Hanson (1993) found that students who had an internal locus of control appeared to value writing tasks and worked harder than students with an external locus of control. Generally, applications of write-to-learn approaches are being more widely used in university/college level science courses than ever before. These traditional and non-traditional writing tasks enhance student learning because they require students to reflect, consolidate, elaborate, reprocess concepts and ideas central to the topic, to hypothesize, interpret, synthesize, and persuade, and hence to develop higher-order thinking and the construction of a deeper understanding of science concepts.

Current trends in language and science education

The constructivist science classroom can be compared with the whole language classroom of the 1980s and 1990s. Science reform in the US promotes an interactive–constructivist interpretation of constructivism that views science as inquiry involving a naïve realist ontology and an evaluativist epistemology (National Research Council, 1996). This compares with the whole language teaching and learning environment in which people search out, describe and explain, where possible, the patterns of language, symbol systems, and communications in a sociocultural context. In both of these interactive–constructive classrooms, people are attempting to become literate by exploring a specific content domain to construct meaning of the big ideas in the discipline and to communicate these ideas to other people. The explorations are self-directed at times, and direct instruction is infused into the explorations on an as-needed basis or just-in-time delivery. This reform context has encouraged integrated explorations of the language arts and science. The research published during the past 10 years has been reviewed as an indication of the current trends and promising endeavors occurring in language and science literacy research; but to keep the organization of this paper consistent, the reviews will consider oral and written language studies separately. Interesting studies involving an integration of oral and written language will be associated with the section that they are most closely aligned.

Current trends in oral language and science

The early years of language and science learning considered in this review emphasized research on oral language as a window into people's understanding and thinking, while de-emphasizing the possibilities that language and the cultural associations could influence the construction of science ideas and that improved language use in science could improve science achievement and scientific reasoning. Lynch and Jones (1995) considered the politically tricky issue of whether all languages and cultural associations are equal in doing science and producing scientific understandings. They found unique differences for abstract and concrete science nouns between three language and cultural groups (English in Australia, and Tagalog and Ilocano in the Philippines) and found differences between the two language groups of the common culture. Lynch and Jones stated:

> These linguistic observations do raise awkward questions about the choice of language of instruction for school science in developing countries. Sociolinguists would argue that there is no such thing as a 'primitive' language and that, in principle, all true languages are sufficiently robust or potentially adequate for 'intellectualization'. This may well be true for dealing with most every day requirements or dealing with the notions of pre-science. However, the language of mature science, certainly in the areas of classical physics and chemistry, as defined in western terms, is extraordinarily condensed with a reliance on highly specialized vocabulary and syntactical constructs. (1995, p. 117)

Exploring the influence of different languages and cultures on science understanding, Sutherland and Dennick (2002) did not find significant differences between Euro-Canadian and Cree Grade 7 students' knowledge about the nature of science, but they did find some cultural differences regarding the Cree students' view of science knowledge that encompassed both science ideas and traditional Cree knowledge about natural events.

Earlier in the present article we proposed that science might require language systems that have both oral and written forms and that are generative and easy to modify or to add concept labels or words. It may be that the language and associated beliefs of some sociocultural groups influence the type of knowledge about nature constructed by these people (e.g., Traditional Ecological Knowledge of the Coastal First Nations (Snively & Corsiglia, 2001), Cree Nation People's Views of Nature of Science (Sutherland & Dennick, 2002)).

Wellington and Osborne (2001) summarized much of the recent research on oral discourse in science learning and concluded that there was little research on the topic; what was found provided reasonable support of oral interactions during science instruction at most levels of schooling; and that student–student discussion, argumentation, and debate did not happen that often in science classes. Newton, Driver, and Osborne (1999) found that less than 5% of class time is devoted to discussion in science courses. Closer analyses of these discussions indicated that much of this discussion is not directed at science understandings, involved dyads of students, and considered rather low-level science ideas. Rodrigues and Bell (1995) found that, within a group of teenage females studying chemistry, the interactive discourse approximated normal conversation with a mix of chemistry concepts and everyday ideas. Kempa and Ayob (1995) found that 40–50% of the science ideas contained in students' writing responses to problem tasks could be attributed to the oral interactions within the small-group discussion prior to the assessment and about 12–23% of the ideas came from the student's private understandings. They found that task-related contributions by a student correlated to the quality of the student's written response, but even the non-speaking participants appropriated ideas from the discussions of other students. They also found that the conceptual content of the oral interactions might have stimulated the private construction or recall of conceptual content for the assessment task.

The cohesion and dialogic nature of discourse are related to the learning effectiveness that occurs in science classrooms. Teachers need to embrace a belief that two-way communications between students and between teachers and students are far more supportive of meaningful science learning than unidirectional speech (Ritchie & Tobin, 2001). The size of the group being talked to rather than talked with probably makes little difference. Frequently, teachers are using the discussion format to lecture to small groups of students about specific ideas, terminology, and explanations. Furthermore, teachers need to ensure that the language and the pattern of communications are developmentally appropriate, shared, relevant, and sufficient (Rodrigues & Thompson, 2001). Discourse and discussion in science classrooms appear to involve persuasion to reveal and consider alternative interpretations of experience and knowledge claims, and strategically placed authoritative discourse to evaluate alternatives and apply shared understanding (Mortimer & Gerais, 1998). Students used collaborative, adversarial, and consensus modes to negotiate common outcomes during open-inquiry physics activities, while the role of teacher varied across the planning (structured guide, coach), data collection (facilitator), and interpretation (structured guide, coach) phases of inquiry (Roychourdhury & Roth, 1996).

Many of the strategies and tasks recommended to improve oral discourse, argumentation, and learning in science are based on the crafts and practices of effective science teachers, lack compelling evidence about their effectiveness, and do not fully demonstrate the connections between improved oral language and science literacy. The research on oral discourse in the past decade appears to have begun to explore how improvement in oral discourse in science might occur and, to a limited extent, whether these discourse improvements might lead to improved science understanding and thinking. A variety of oral discourse patterns among teachers and students – including teacher-led large-group discussions utilizing a Socratic method, unstructured peer interactions in small-group laboratory settings, and semi-structured small-group discussions, have been suggested for constructivist science classrooms. Like an effective whole language teacher who uses direct instruction on language strategies and structured experiences focused on increasing the quality and quantity of oral interactions embedded in the student-centered inquiries into literature and language, the effective constructivist science teacher uses teacher-generated questions, knowledge-building tasks, and explicit instruction to enhance and promote oral discourse and argumentation embedded in science inquiry.

Teacher-initiated questioning and student-generated questions are the central focus of several science educators and researchers. The role of teacher-initiated questions and questioning strategies has again become the central focus of science classroom research in terms of scaffolding active inquiry and knowledge construction. Much interest has been expressed on re-visiting questioning strategies and wait-time and on exploring productive questioning (Martens, 1999) since questioning can often be the key influence in successful constructivist classrooms. The role of questions in accessing and challenging students'prior knowledge, scaffolding inquiry, and facilitating knowledge building have once again become a central issue in science teaching and learning (Coburn, 1998). Much is known about the value of question structure, question level, and wait-time and how sequential questions can guide sharing of ideas, interpretation of experiences, knowledge construction, verification of alternative interpretations, and the application and integration of new knowledge in the consolidation phase of inquiry (Penick, Crow, & Bonnstetter, 1996). Less is known about how questions drive the active inquiry, problem setting, data collections, and evidence analysis in the exploration phase. Martens (1999) proposed a new schema for teacher-initiated or student-initiated questions to scaffold students' inquiry and epistemic actions – focusing, data collection, comparison, action, problem posing, and reasoning during inquiry in small-group environments. She identified functional types of questions designed to promote inquiry procedures, task completion, data interpretation, reasoning, and other epistemic actions in a more collaborative manner.

Ultimately, constructivist teachers want students to initiate and guide their own inquiries and knowledge construction. Students are able to generate their own basic information questions, but are less likely to generate wonderment questions that initiate discussion about hypotheses, predictions, experiments, and explanations (Chin, Brown, & Bruce, 2002). Students are likely to generate a wider range and greater number of wonderment questions in problem-solving activities. The interrogation of text utilizing student-generated questions has been shown to improve with instruction and to enhance reading comprehension (Costa, Caldeira, Gallastegui, & Otero, 2000). Explicit instruction on the characteristics of researchable questions for high-interest and low-interest topics improves the quality of research questions generated across the interest level of science topics for Grade 7 students (Cuccio-Scherrigue & Steiner, 2000).

Wellington and Osborne (2001) described several structured experiences and tasks to support students' interactions, discussions, and debates. They suggested the use of collaborative concept mapping activities, structured critical instances involving common misconceptions, and the use of directed activities related to texts to structure and guide students in small-group activities and discussions. These tasks appear to help structure oral interactions, focus discussions, construct arguments (claims, evidence and warrants), develop explanations, and promote conceptual understanding. Roth and Roychourdhury (1994) used co-constructed concept maps to focus the oral discourse and to promote the construction of science understanding.

Newton *et al.* (1999) delineated the necessary conditions for meaningful argumentation that promotes better understanding of argument and of the science concepts involved. Several studies have illustrated potential in terms of helping teachers find ways to promote argumentation and in terms of demonstrating higher quality arguments in small groups, but a direct relationship to improved science achievement has not been established (Osborne, Simon, & Erduran, 2002). The quality of argument appears related to the abstractness of the central problem and hypothesis; and students frequently generate faulty arguments, missing or confusing elements, non-verifiable hypotheses, and failure to consider alternative hypotheses (Lawson, 2002). Students' simple arguments can be improved with explicit instruction (Zohar & Nemet, 2002). Debates, role-plays and structured controversies appear to provide rich environments for explicit instruction and development of argument abilities in presenting, justifying, and defending a knowledge claim in science, technology, society and environment issues (Patronis, Potari, & Spiliotopoulou, 1999; Simonneaux, 2001).

Rivard and Straw (2000) explored the interaction among talking, writing, and science learning. They found that small-group discussion in conjunction with structured writing tasks appeared to produce the highest achievement on a multiple-choice examination covering the target concepts. They found that talking in support of writing and science learning was especially helpful for low achieving-students.

Current trends in science reading

As noted in the previous section on reading, researchers who study reading scientific texts assume a text-processing model that is interactive in nature. That is, the mental representations of texts that readers construct are a result of the surface structure of the text, readers' prior knowledge, and the concurrent experiences in the sociocultural context (Gee, 2000). Depending upon the expertise of the reader, this could include general knowledge of the domain (e.g. biology), the specific topic of the piece (e.g. the genome project), rules of evidence and argumentation used in the scientific community, the types of texts (genres) used to communicate about science, and intertextuality; that is, how new knowledge claims made in the document under consideration relate to previous claims made in the scientific literature. Indeed, one could characterize scientific inquiry as 'a dialectical process in which one grapples with the ideas, thoughts, and reasoning of others often through the medium of written texts' (Goldman & Bisanz, 2002, p. 20).

Three trends in the literature can be used to characterize the work conducted between 1994 and 2003 in a way that highlights what is known and what challenges remain for future researchers. The first trend is that research on reading of scientific 'texts' is no longer synonymous with reading textbooks designed for students, although research on textbooks continued. Reports about scientific and medical research are pervasive in the media, including the Internet; and even people who pursue a career in science cannot follow the primary literature in all scientific disciplines. Furthermore, the frontier science that appears in media reports is often quite different from the uncontroversial, reliable, and established science presented in textbooks (Penney, Norris, & Phillips, 2002; Zimmerman, Bisanz, & Bisanz, 1998; Zimmerman, Bisanz, Bisanz, Klein, & Klein, 2001). Awareness of the importance of this form of reading science to life-long learning has led researchers to begin to study how well people read and evaluate accounts of research that occur in media reports (Korpan, Bisanz, Bisanz, & Henderson, 1997; Norris & Phillips, 1994; Phillips & Norris, 1999; Zimmerman *et al.*, 2001). Researchers conducting this and related research have begun to argue that reading, comprehending, and evaluating media reports and diverse forms of scientific writing are part of the collection of abilities, strategies, and metacognition that individuals need to be scientifically literate in the fundamental sense (Goldman & Bisanz, 2002; Holliday *et al.*, 1994; Koch & Eckstein, 1995; Mason & Boscolo, 2002). The second trend is a growing recognition that science texts are not a uniform set of documents; rather, they can be differentiated with respect to the sociocultural roles or functions they play in society. In addition, differences in function are associated with differences in form, both of which have implications for the interactive and constructive processes that occur when science texts are read for specific purposes. The third trend, already evident in the section on 'Scientists as Language Users', involves attempts to consider the implications of the expert-novice distinction when considering the levels of scientific literacy that may be appropriate for the population at large.

Goldman and Bisanz (2002) identified three major functions or roles for documents that communicate about scientific information in society; namely, communicating among scientists, popularizing information generated in the scientific community, and providing formal instruction to prepare individuals to enter the scientific community or become scientifically literate citizens. These three functions serve the needs of distinct discourse communities, specifically, scientists, the general public, and students. Goldman and Bisanz identified a range of forms or genres associated with each function, as well as the genres that are central to accomplishing the goals of each community. For example, within the scientific community, two broad groups of genre can be distinguished: formative and integrative. Formative genres shape scientists' thinking, reflect the cutting edge of scientific fields, and range from the personal (e.g. bench/field notes) to the public (refereed journal articles). Integrative genres are syntheses of what is widely known and accepted about a topic (canonical science) and include genres such as the refereed review article. The dominant genre in the scientific community is the report of empirical research. Among the genres intended to popularize science for the public, again two broad subfunctions can be identified; namely, raising public awareness and increasing public understanding. Genres intended to raise public awareness range from press releases and news briefs to science fiction; genres intended to increase public understanding have an instructional intent and range from feature articles and reference books to topic-specific informational Web sites. Goldman and Bisanz assert that the central genre for this function is the Journalistic Reported Version of the Research Report (JRV) because it can be written with a goal of raising awareness or increasing understanding. Finally, genres written for students and instruction are designed to reflect curriculum themes or emphases and include textbooks, laboratory workbooks, and newly emerging genres such as educational websites. However, for reasons that should be clear, the dominant genre remains the textbook designed for classroom use. Textbooks are often written to support such curricular themes as understanding science content, including facts, concepts, and processes, and STSE connections, leaving laboratory workbooks or exercises to support learning inquiry processes.

Importantly, although each of these genres has *intended audiences*, they can be, and are being, read by *incidental audiences* for their own purposes. Genres written to serve a function within a specific discourse community being read by incidental audiences have implications for understanding and learning processes that need to be understood when considering the goal of enhancing 'scientific literacy for all people' in its fundamental sense. Considering the wide range of scientific texts that could be examined, much of the extant research is focused on study of the three central functions: empirical research reports, JRVs, and textbooks. Other than the work described previously on scientists reading journal articles, readers in these studies are generally novices and, more specifically, students. And with perhaps the exception of research on textbooks, the overwhelming sense one has in reviewing this literature is how understudied the reading of science texts by novice or experts is altogether!

In the case of novices reading empirical research reports there appear to be only a few studies, all conducted during the earlier era of research on reading science. These studies provide evidence that the schema (structure or organization) for a research report functions much like the well-studied narrative schema to guide processing and memory and that instruction intended to give students information on the organization of journal articles can enhance memory from text. However, like scientists reading on topics outside their specialization, students are incidental audiences with a lack of domain knowledge to guide processing. They are further handicapped by lack of any sophisticated knowledge of the structure of research reports and the role of texts within the scientific community. As a result, reading empirical reports for their own purposes, such novices would probably read linearly, have difficulty identifying the functions of the text both at the level of sections of the report and sentences within sections, use limited comprehension strategies, and have no basis for evaluating knowledge claims made within the report (Goldman & Bisanz, 2002; Yore, Craig, & Maguire, 1998).

Speculations about novices' performance reading empirical reports are possible only because of the work conducted in the past decade on students reading popularizations, especially variants of the JRV, including news briefs and feature articles that might be encountered in newspapers or magazines. Alexander, Kulikowich, and Schulze (1994) found that undergraduate and graduate students who had greater knowledge of physics provided higher ratings for interest in reports focused on physics than students who had low knowledge. Thus, in everyday contexts, knowledge of domain may help account for article selection, reader engagement, the quality of mental representations constructed, and, as a result, the potential for informal learning. Interest can also be affected by characteristics of these texts (Wade, Buxton, & Kelly, 1999).

There are also studies providing evidence that high school students with strong backgrounds in science and university students have limited knowledge of the elements of scientific argumentation, the features of research, and the nature of science that is important for understanding and judging the potential credibility of the research and knowledge claims described in such reports. Norris and Phillips (1994) had secondary school students with good science backgrounds judge the scientific status of sentences (e.g. causal claim, observation, method) as well as their roles in the scientific argumentation (e.g. justification, evidence, conclusion) in newspaper and magazine reports. No more than one-half of the students could identify the scientific status and role of statements in the arguments the authors were developing. These students attributed a higher degree of certainty to the statements than was expressed by the authors. Furthermore, these deficiencies appeared to be unrelated to students' self-assessments of their knowledge, interests, and difficulty reading (Norris, Phillips, & Korpan, 2003). Korpan *et al.* (1997) examined the additional types of information that undergraduates felt was important to assessing the credibility of research featured in brief media-style reports. Students most frequently requested additional information about how the research was conducted and why the results might have occurred. Fewer requests were made for information about what was found, who conducted the research, and where it was conducted. The latter two types of information can be correlates of quality when details about methodology are lacking. Least frequent were requests for information about related research, information that reflects the nature of progress in the field and the established science to augment the current evidence. In a related study, Zimmerman *et al.* (1998) found that experts considering the credibility of brief media-style reports differed from students in placing high value on social context information (e.g. funding agencies, quality of publication outlet, potential biases of researchers) and related research. This difference is probably attributable to experts' knowledge of the nature of science and norms for establishing knowledge claims. Both experts and students emphasized the importance of methodological information. Finally, Phillips and Norris (1999) provided evidence that, when reading newspaper and magazine reports, university students adopt processing strategies or stances toward these texts that are accepting, rather than critical. The latter involves balancing prior beliefs with text information to arrive at an interpretation of meaning, whereas the former allows text information to overwhelm prior beliefs. The critical stance has the most promise for life-long learning.

Also new in the past decade is exploratory research focused on the evaluation of scientific arguments where the World Wide Web is the medium. In fact, the spread of ICT may prove to be one of the most potent factors in motivating science educators to consider the need to teach students to read a wide variety of scientific writing. The Internet is sweeping aside the traditional institutional gatekeepers of science (e.g. media outlets, publishing houses, libraries, and approved educational textbooks), overnight raising the importance for science literacy in its fundamental sense. The challenges posed to novices reading science in this complex ICT environment are self-evident. Brem, Russell, and Weems (2001) asked Grade 9, Grade 11, and Grade 12 students to apply the criteria of credibility, accuracy, reasonableness, and support or evidence to evaluate the scientific claims made on six websites. The sites were hoaxes, legitimate but weak sites, and legitimate but stronger sites. As is typical of the World Wide Web, all of the sites had missing information, knowledge requirements, and little support to assist laypersons in locating resources that might facilitate evaluation. Despite an instructional scaffolding of explicit instruction and access to other websites, within a critical thinking module, a number of limitations in students' evaluation were apparent. Student assessments failed to distinguish the quality of the science from the quality of the reporting. They demonstrated an absolutist view of science, weak metacognition, and equated greater detail with greater accuracy. Furthermore, students were not inclined to visit other websites to gather collaborating evidence.

This study documents some of the challenges that readers encounter evaluating science on the Web, once sites are identified. Typically, however, readers must both identify and evaluate websites. A study of Grade 6 students engaged in an inquiry exercise that involved seeking answers to their own questions about a science topic suggested that 'students overemphasized the search aspect of the process, treating the search process itself as the centerpiece of the work they did' (Wallace, Kupperman, Krajcik, & Soloway, 2000, p. 92). For these students, reading and evaluation amounted to taking quick glimpses at content pages to find words that matched the answers they expected to find, without evaluating the source or content, and then shifting swiftly back to pages with search engine results – a variant of the time-honored strategy of answering questions by matching words in italics or bold print, table of contents, or index of a book.

An area where the public commonly uses the Web in everyday life is to seek information about health (Statistics Canada, 2001). A single-subject study illustrated some of the challenges faced by an expert reader in this situation (Bisanz, 2000). The participant was reading outside her area of expertise to develop a list of questions from medical research to discuss with a physician related to a treatment decision. The issue of how to identify credible and related topical websites shaped the search strategy from the outset. Seven different types of scientific writing were encountered, including documents written by researchers, health professionals, reporters, and government regulators. Meaningful interpretation of these texts required knowledge of the nature of expertise and activities of the discourse communities that generated these documents as well as the types of confounding variables and boundary conditions that frequently limit the types of generalizations that can be drawn from research on humans. Both this study and research conducted with university students reading on the Web with the purpose of making a treatment decision when given a similar medical scenario (Bisanz, Kachan, Guilbert, Bisanz, & Sadler-Takach, 2002) suggest that, despite its hazards, the Web can be a powerful tool for learning and improving the quality of questions individuals bring to the decision-making process. Given the potential importance of ICT, it is not surprising that researchers have begun detailed study of the cognitive strategies and processes that learners engage in when reading science texts on the Web and how readers' goals, interest, and knowledge influence these strategies, processes, and learning outcomes (Goldman & Wiley, 2002). However, the types of knowledge about the nature of science and various forms of scientific writing required to use this tool effectively are not typically the focus of either secondary or post-secondary science education.

As noted previously, during this decade, research on textbooks continued, often focused on the aspects of textbooks devoted to science content, cultural perspectives, gender, and understanding facts, concepts, and processes. Although students' difficulties in such texts were clear in the earlier reading research, the theories of reading and text processing and lines of research emerging from the applied cognitive sciences have helped clarify some of the sources of their handicaps (Graesser, Leòn, & Otero, 2002). For example, studies of students in middle school (Craig & Yore, 1995; Yore *et al.*, 1998) revealed that their knowledge about reading science, metacognitive awareness, was only partially developed and the strategies they used to repair comprehension failures were limited and not well adapted to science text. Students' approaches to dealing with comprehension difficulties were predominantly bottom-up and text-driven or involved seeking help from the teacher. They seemed largely unaware that prior knowledge might help resolve difficulties. Added to these problems is that students have little prior knowledge about the science topics and many need to construct interpretations from scratch or they may have naïve theories or misconceptions that interfere with information presented in the text (Alexander & Kulikowich, 1994). Worse yet, imprecise or inappropriate language may even be responsible for some of the misconceptions (for example, Sanger & Greenbowe, 1997). Readers may also lack knowledge of the organizational patterns of such texts. In addition, teachers' values and explanations can enhance, but sometimes detract from, learning from textbooks (Alexander & Kulikowich, 1994). In the face of such handicaps and the amount of material to be learned, reading textbooks can reduce to a strategy of memorizing information perceived to be important for tests (Goldman & Bisanz, 2002).

Guided by such insights, research has been conducted to (a) identify ways to redesign textbooks to enhance comprehension, (b) assist readers to develop strategies that can facilitate meaningful processing, and (c) compare designed inquiry environments for classrooms involving novel use of a variety of science texts or innovative genres to standard instruction with textbooks. A number of the methods for altering textbooks in ways that increase comprehensibility were explored, some of which were extensions of lines of research initiated at the end of the period of reading research described earlier and some of which were novel. Examples of this approach include making explicit the logical and causal structure of information and explanatory relations among claims and evidence (Mayer, Bove, Bryman, Mars, & Tapango, 1996; McNamara, Kintsch, Songer, & Kintsch, 1996), adding examples that precede the introduction of new terms (Musheno & Lawson, 1999) or signals such as section headings or pointer words (Mautone & Mayer, 2001), including refutations of inappropriate conceptions that learners might hold and explaining why they are less appropriate than alternative conceptions (Hynd & Guzzetti, 1998), and use of analogies (Glynn, Law, & Doster, 1998; Glynn & Takahashi, 1998). Some of these researchers studied the conditions under which text and visual formats function to enhance understanding (Glynn *et al.*, 1998; Hannas & Hyönä, 1999; Harp & Mayer, 1997; Iding, 1997; Mayer, 2002; Mayer *et al.*, 1996). Text structure, comprehension monitoring, and linguistic devices need to be understood more fully (Alexander & Kulikowich, 1994; Farragher & Yore, 1997; Hannas & Hyönä, 1999; Iding, 1997; Guzzetti, Williams, Skeels, & Wu, 1997; Thiele & Treagust, 1994). Ideally, textbooks would be customized so that the coherence of the text would be challenging enough to stimulate active processing but not so difficult as to cause a breakdown in comprehension (McNamara *et al.*, 1996).

Illustrations of approaches that encourage students to adopt more effective and meaningful processing strategies include teaching awareness of text structure and the use of graphic organizers (Spiegel & Barufaldi, 1994) as well as generating explanations (Chi, de Leeuw, Chiu, & LaVancher, 1994). Indeed, the self-explanation effect has been demonstrated over a variety of science-related expository materials (Coleman, Brown, & Rivkin, 1997; Coté & Goldman, 1999; Coté, Goldman, & Saul, 1998). Research has also been conducted on the characteristics of students that are likely related to students' ability to learn from textbooks and other types of science-related expository texts; one instance being the sophistication of their epistemological beliefs about learning (Chan & Sachs, 2001; Qian & Alvermann, 1995). The potential of explicit comprehension strategies, metacognition awareness, and executive control embedded in science inquiry has demonstrated mixed results on improved reading comprehension, metacognition, and science achievement (Holden & Yore, 1996; Spence, Yore, & Williams, 1999). Examples of approaches that involve comparing designed inquiry environments for classrooms, using a variety of science texts or innovative genres with standard instruction with textbooks include Concept Oriented Reading Instruction (Guthrie, Van Meter, Hancock, Alao, Anderson, & McCann, 1998), and Palincsar and Magnussen's (2001) work using a scientist's notebook in the classroom. Notable in these interventions is the use of texts to extend and enrich elementary school children's thinking about science phenomena that they have begun to investigate first hand.

In summarizing research on textbooks, Goldman and Bisanz concluded that readers need to bring a lot of active processing strategies to these texts and that:

> readers in formal educational settings need to engage in less memorizing and adopt more critical and active approaches to science texts, more akin to the stance of practicing scientists when reading professional genres. (2002, p. 42)

However, even if students could be taught to read modern textbooks from a more active, strategic, and metacognitive stance or if textbooks could be re-designed to better support such a stance, we must still return to the question raised by researchers focused in reading science in the media: Will reading textbooks ever be sufficient to prepare students for the wide range of science writing they will encounter over their life-times? The unique features of the free flow and unedited World Wide Web increase the need for readers with sufficient domain and topic knowledge, metacognitive awareness and executive control of their reading comprehension, and proficiency with the required strategies. Over 25 years of research on language and science, it has become very apparent that the science classroom and the school are places that can help prepare students to engage meaningfully with the real world. Preparing students to be critical and reflective science readers in that world, however, will probably require a change in curricular emphasis.

Current trends in writing-to-learn science

The understanding of the knowledge-building model of science writing (Keys, 1999) and constructivist science teaching approaches have generated synergy at a theoretical level, but the actual application of writing as a learning process within science classrooms has only really begun to gain prominence (Yore, 2000). Patterson (2001, p. 15) indicated that 'The use of writing as a means of developing pupils' understanding is very rarely considered in schools'. If the emphasis on broadened conceptions of science literacy is to be achieved, then clearly there has to be continued research into how best to implement writing as a learning tool to enhance writers' knowledge about science and written discourse in science.

Prain and Hand (1996) put forward a model for adapting writing for science classrooms. The model defines five separate but inter-related theoretical and pedagogical components associated with a writing task: writing type, topic, purpose, production method, and audience. Hand, Prain, Lawrence, and Yore (1999) outlined an implementation framework for writing in science that dealt with essential theoretical elements: the nature of science, epistemic ways of knowing, patterns of argumentation, plausible reasoning, big ideas of science, communications, and evidence. Collectively, these components and elements of writing within science classrooms move past the older, narrower conceptions of science literacy as merely reading and replicating science knowledge toward the combined derived and fundamental senses of science literacy. Studies of scientists as writers and novice scientists becoming writers indicated that they view writing as an integral part of doing science as well as reporting science to various audiences (Chaopricha, 1997; Florence, 2001, Yore, Florence, *et al.*, 2002).

Writing-to-learn strategies are viewed as being critical in the process of helping students understand science as a discipline and constructing rich understandings of the science concepts being studied. Emmel, in discussing the importance of writing as an epistemic process, summarizes the argument by stating that:

> if [the students] cannot understand the importance of the initial epistemological stages of this journey of knowing and writing, how can they progress to the final stages of knowing what they think and why, and know the entire process as one of their own creation. (1994, p. 18)

Writing is viewed as a learning tool (technology) that involves students in far more than mere demonstration of knowledge. Rather, the act of writing in science is seen as a process of constructing understanding and building knowledge: the minds-on complement to hands-on inquiries.

Implementation studies to date have involved students using writing as a learning tool in situations varying between traditional writing tasks, altered traditional tasks, and non-traditional writing tasks. While there is a need to conduct studies on using writing to learn strategies that differ from traditional uses, importance is placed on ensuring that the content and the nature of science are maintained. Students are using claims, evidence, and warrants to argue, persuade, and explain to different audiences the science content under review and that there is not an attempt to turn science literacy into science fiction.

The later years of this survey revealed increased research interest in and classroom use of writing-to-learn science at all levels of education. University and college level activity appears to have been stimulated by two independent factors – institutional requirements about writing-intensive courses directed at the quality of written communications for graduation, and the perceived power of writing in service of science learning. Hallowell and Holland stated:

> scientific illiteracy among college students is a persistent problem . . . yet the need to understand science principles and to be able to make judgments about the value of scientific knowledge and research has never been greater. (1998, p. 29)

Science literacy and the related print-based communication requirements need to address the dual goals 'writing-to-learn science and technical science writing' of literate adults and literate science professionals. Chinn and Hilgers (2000) found that professors who assumed the role of collaborator rather than strictly the role of evaluator produced better quality student writing and student attitudes toward science writing and the science course.

The use of writing-to-learn strategies in secondary schools has become much more widespread in science classrooms that de-emphasize the exclusive priority of science knowledge, that promote constructivist approaches to teaching and learning, and that stress a more balanced vision of science literacy. Other studies in secondary science have focused on effective teaching of the genres of science, modified version of laboratory reports, collaborative classroom writing through computerized journals (Audet, Hickman, & Dobrynina, 1996), and diversification of writing genres (Hildebrand, 1998; Sutton, 1996).

Most of the increased interest for science writing in the elementary schools has to do with the willingness of elementary teachers to expand their language arts program across the curriculum (Baker, 1996). Contemporary approaches in language arts involve establishing a language community in the classroom that addresses a wider variety of authentic speaking, listening, reading, writing, representing, and viewing tasks (National Council of Teachers of English and International Reading Association, 1996). There is some hesitation to infuse these language tasks into science and mathematics, but the recognition that numeracy and science literacy involves communications to inform others and persuade people to take informed action has helped encourage teachers to include writing-to-learn activities in their mathematics and science programs, not only those with strong language arts backgrounds.

Traditional writing tasks in science have centered on such activities as keeping accurate records, completing laboratory reports, and demonstrating an understanding of concepts for assessment purposes. These writing tasks do not explicitly place strong emphasis on students moving beyond the duplication of knowledge. Some studies done in universities and colleges highlight this emphasis on replication of the norm. Kelly and Takao (2002) examined students' epistemic arguments while writing traditional technical reports in an oceanography course. Koprowski (1997) infused writing instruction, writing assignments, and peer-review into science courses. Rice developed an advanced stand-alone scientific writing course designed for upper-level science majors in which he served as 'guide, coach, cheerleader, critic and occasionally referee' (1998, p. 268). Central to the success of the course were specific instruction and assignments that provided insights into the different genre scientists use to communicate with different audiences. Rice infused explicit instruction on grammar, appropriate voice, word usage and choice, sentence structure, and logical development at opportune times as needs arose.

The alteration of traditional writing tasks was based on the understanding that transformation of ideas occurs during the write–react–revise phases of argumentation and that novice writers do not emphasize the write–revise sequence in their writing process. These understandings promoted the development of sequential writing tasks and structured tasks that promoted transformation of ideas during the holistic writing process (Hand *et al.*, 2001). They found that using a series of writing tasks and authentic audiences during a science unit enhanced students' higher-level science achievement. The Science Writing Heuristic (SWH) for laboratory activities incorporates both a teacher and student component in a manner that tries to turn the typical cookbook school science laboratory activity into an activity more closely aligned to what occurs in actual science laboratories (Hand & Keys, 1999). In place of such headings as hypothesis, procedures, observations, results and discussions, the students are required to answer questions such as What is my question?, What did I do?, What did I see?, What is my claim?, What is my evidence?, What do others say (i.e. peers or the textbook)?, and Did I change my ideas? The intent of the questions is to change the laboratory activity from a set of procedures that demonstrate knowledge into something that requires a much more active epistemic role for students. A critical component is the teacher's role in implementation because there is a need for students to negotiate meaning in different sociocultural contexts: individual, small groups, and whole class settings. Students are not only required to generate individual meaning, but to also engage in public discussions about their activities and share their understandings in order to reach consensus on the knowledge constructed within the established science knowledge. Great importance is placed on consulting the authorized version of the concept only after there has been an attempt to engage the concepts. Through writing, talking and reading, students are able to construct a much richer understanding of the science within the laboratory activity.

Studies to date using the SWH approach have shown very positive results for these types of altered traditional writing tasks. Rudd, Greenbowe, Hand, and Legge (2001) found significant differences between freshman chemistry students studying equilibrium in favor of the treatment group using the SWH for performance on conceptual questions of an examination related to the topic. Not only was the student performance improved using the SWH procedures, but also the quality of their written answers revealed much greater use of the chemistry terminology. Other studies at the Year 7 and Year 10 levels produced similar results. Year 7 students' responses to an end-of-unit test indicated that the treatment students performed significantly better than the control students on both lower-order items and higher-order conceptual items (Keys, Yang, Hand, & Hohenshell, 2001). Year 10 students' performances were similar in that the treatment students' performances on conceptual questions were also significantly higher than the control students' performance (Hohenshell, Hand, & Rudd, 2002).

Non-traditional writing tasks require students to address a broader group of audiences than just the teacher and a different range of purposes using a variety of writing types. Students can be involved in such writing activities as poetry (Watts, 2001), anthropomorphic writing (Hildebrand, 2002), and writing for peers (Couzijn & Rijlaarsdam, 2002). Such writing provides opportunities for students to engage the central science concepts at a personal level and to inform, explain, and clarify concepts for a non-expert readership, and hence to themselves. These writing tasks require students to engage the language of science and the science concepts in a manner not normally dealt with in school classrooms. While there are often simple traditional and non-traditional writing tasks in the end of chapter questions, such as write an explanation of what causes the seasons or write a story about the day in the life of a red blood cell, there is much more required than simply asking students to complete the task. Patterson (2001) believed that, when asking students to undertake writing tasks, there is a need to scaffold their attempts; that is, students need to be provided with structured support (concept mapping) and explicit instruction on how to transform their conceptual network into arguments and explanations.

Scaffolding novice writers' planning and pre-writing composition activities have shown positive potential. Hand, Prain, and Hohenshell (2000) implemented a study to examine the benefits of using planned writing experiences with Year 10 students who were asked to write a textbook explanation for Year 7 students. The audience was real, in that the Year 7 students were asked to evaluate the textbook explanations produced by the Year 10 students. The Year 10 students' performance on higher-order conceptual questions of the unit test who underwent a planned writing experience compared with a delayed planning experience was significantly better. Planning and pre-writing activities more closely reflected scientists' writing and they made a difference in the students' science achievement. Similar results were obtained for Year 11 chemistry students who were asked to write business letters to Year 8 students explaining the concepts of stoichiometry (Yang, Hand, & Bruxvoort, 2002).

Several classroom studies have demonstrated the potential effectiveness of writing in science to improve writing performance, science achievement, and attitudes toward science and writing. The use of culminating writing activities can encourage students to reflect, integrate, and elaborate on their science understandings developed during verbal interactions in cooperative groups. Peer-review and jigsaw writing activities can be effective. A series of writing frames has supported young writers in their early attempts to use factual genre, sequential writing tasks achieve revision without repetition, and the SWH has promoted quality arguments and high-order learning (Keys, Hand, Prain, & Collins, 1999; Tucknott & Yore, 1999; Wray & Lewis, 1997). The use of teacher scaffolding and structured frames allowed students to develop discourse knowledge about the specific genre. The results indicated that teachers need to use a series of writing tasks that require students to transform their ideas and writing form, and that these sequential tasks increase the students' higher-level thinking, quality of argument, and science achievement. The use of pre-writing activities and writing tasks to improve science understanding and to enhance compare–contrast thinking has demonstrated potential (Patterson, 2001).

> Prewriting activities, particularly those including visual aids, focus writing so that students can successfully compare and contrast information. (Shelley, 1998, p. 38)

Here again, the structured tasks are sequenced to require students to process, interpret, transform, and internalize information, not just copy textual materials.

Promises for the future

The importance of science (people's attempt to search out, describe, and explain patterns of events in the natural world) as inquiry emphasized in the current international reform documents must also emphasize science as argument that proposes knowledge claims based on evidence from nature accessed in current inquiries and augmented by canonical science from former inquiries. Wellington and Osborne stated:

> Put simply, it is because learning to think is learning to reason. Learning to reason requires the ability to use the ideas and language of science so that the student [at all levels of expertise] learns how to use new words in the appropriate manner, and to use familiar words with their accepted scientific meanings . . . Moreover, learning to reason in science requires the ability to construct arguments that link evidence and empirical data to ideas and theories. Practical work alone is insufficient to create a bridge between observation and the ideas of science. (2001, p. 83)

Scientists and students of science alike use oral and written language to do science, to construct new understandings of science ideas, to access and comprehend established science ideas stored in various information sources, and to inform and persuade other scientists and people about science (Florence, 2001; Yore *et al.*, 2001; Yore, Florence, *et al.*, 2002; Yore, Hand, *et al.*, 2002). Language is a technology and a tool to facilitate thinking and plausible reasoning, to make sense of events in the natural world, and to solve communication problems.

As we have demonstrated, current research on language and science is a product of interdisciplinary understandings emerging in the applied cognitive sciences and forces at work within the science education community itself, such as the influence of the constructivist perspective and the trend to use ICT. Yet the researchers in these diverse discourse communities who share common interests in the study of language and science, much like the inhabitants of separate islands, are often passionately engaged in their scholarly activities, unaware of the significance and relevance of each other's work. Communication of ideas across community boundaries is fruitful and highly rewarding, but requires the time and patience needed to create common meanings from specialized vocabularies. More rapid progress in this important area of science education will depend upon raising greater general awareness of the importance and value of this type of interdisciplinary communication and a commitment by the researchers themselves to forge the interdisciplinary alliances that will bring this area of research and practice centre stage. Recent conferences funded by the National Science Foundation (US) held at the University of Maryland, Baltimore, MD, USA (Saul, 2001) and at the University of Victoria, Victoria, BC, Canada (Hand & Yore, 2002) addressed the needs to bridge the cultures of research and practice and to establish interdisciplinary, international, interinstitutional, and inter-generational networks of researchers and teachers interested in the connections between language literacy and science literacy.

Future research will need to utilize a recursive approach to document and explain literate practices in science as demonstrated in research cultures, exemplar classrooms, and controlled experimental settings. The current understanding of language in the service of science is informed both by the practices of effective teachers of science, the craft, and by the research of applied cognitive scientists. Research cultures in laboratories and learning environments in exemplar classrooms illustrate a variety of language modes – symbols, mathematics, words, visual adjuncts and gestures – and a range of primary, secondary, and tertiary information sources – databases, research journals, and conference presentations. These modes and sources involve both face-to-face and at-a-distance ICT communications. The strategic use and metacognition of the associated language practices must be more fully explored in natural and controlled settings, and these results need to be moved to classrooms and other instructional settings. A guiding principle for the transfer of these results, instructional practices, and literate practices in science should be to embed the literacy instruction into authentic scientific inquiry to construct new understandings similar to how an effective research supervisors' attempts to enculturate a novice scientist into a scientific discourse community (Florence, 2001).

Promising practices observed in exemplar learning contexts and explored in research settings are:

1. Critical listening and reading of multi-media sources.
2. Effective oral and written multi-media presentations.
3. Effective discussions, debates, and arguments to establish knowledge claims based on evidence and augmented with established science ideas.
   - Productive questioning.
   - Debates and structured controversy.
   - Written arguments.
4. Strategies to improve the quality of explanations.
5. Effective ICT knowledge building communities (Bereiter, 2002): Knowledge Forum (Scardamalia & Bereiter, 1994), Knowledge Integration Environment (Linn, 2000), and so on.

Successful implementation of these instructional activities, strategies, environments, and technologies will require supportive scaffoldings for the teachers of science and their students. Implementation will require several steps. First, the science education community must further verify the ecological validity and robustness of these approaches. Next, the science education community must convince teachers of science that these approaches are legitimate ways of achieving science literacy in both the derived and fundamental senses. Finally, the science education community must incorporate these approaches into their teacher education programs and help practicing teachers infuse these approaches into science inquiry teaching (modified learning cycle, project-based instruction, etc.) and traditional programs. The challenges in research and practice that lie ahead are many but, if they are met successfully, we will achieve a new, more authentic view of science among our citizens; and they will be engaged in everyday life, empowered with scientific literacy in not only its derived, but also its fundamental sense.

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