SCIENCE FOR THE NEXT GENERATION

PREPARING FOR THE NEW STANDARDS

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Table of Contents

FOREWORD xi
Early Science Education: Answering the Question, 'Why?'
Arne Duncan

INTRODUCTION xiii
The Importance of Science in Elementary School
Dudley Herschbach

PREFACE xv
Francis Q. Eberle

BOOK OVERVIEW xvii
Thomas O'Brien

I. WHAT IS SCIENCE?

Introduction: *Teaching Science in Elementary School: Turning Today's Children into Tomorrow's Leaders* 2
Steven Chu

CHAPTER 1 ***What is Science?*** 3
Marshall L. Grant , William Banko, and Dario Capasso

II. THE NEW SCIENCE OF LEARNING

Introduction: *Illuminating Minds* 12
Michael Gazzaniga

CHAPTER 2 ***Five Minds for the Future*** 13
Howard Gardner

CHAPTER 3 ***How We Model the Complexities of The World: Learning & Memory: Systems & Function*** 27
Anthony J. Greene

III. THE NEW SCIENCE OF LEARNING IN THE CLASSROOM

Introduction: *Science Is Fun* 46
Chuck Niederriter

CHAPTER 4 ***What Teachers Do to Engage Their Students in Learning*** 48
Abby B. Bergman

IV. A FRAMEWORK FOR SCIENCE EDUCATION

Introduction: *Redefining Science Education* 66
Bruce Alberts

CHAPTER 5 ***High Expectations for All*** 67
Robert Rothman

CHAPTER 6 ***From Framework to Standards*** 87
Lesley Quattrone

V. LITERACY AND SCIENCE

Introduction: *Science and the Educated Person* 98
Steven Pinker

CHAPTER 7 ***Science? Literacy? Synergy!*** 99
Gina N. Cervetti, P. David Pearson, Cynthia L. Greenleaf, Elizabeth Birr Moje

VI. USING THE ELEMENTS OF THE *FRAMEWORK* TO DESIGN YOUR OWN LESSONS

Introduction: *Science at the Center* 124
Bruce Alberts

CHAPTER 8 **"5 E(z)" Guidelines for Designing Research-Informed Science Lesson Sequences** 126
Thomas O'Brien

VII. THE NEXT GENERATION SCIENCE STANDARDS IN THE CLASSROOM

Introduction: *The Importance of Teaching Science in Elementary School* 138
Eric R. Kandel

CHAPTER 9 ***Sample 5E Mini-Units for Grades K-5*** 139

Introduction: *Connections* 139
Patricia B. Molloy

- **Physical Sciences**

  What's All the Noise About? The Science of Sound: A 5E Mini-Unit 141
  Helen Pashley

  Where's My Sugar - Experimenting with Dissolving: A 5E Mini-Unit 154
  Jenay Sharp Leach

- **Life Sciences**

  Zoogle Zoology: A 5E Mini-Unit 169
  Jennifer Baxter

  Animal Groups: A 5E Mini-Unit 188
  Helen Pashley

  Demystifying Decomposers 201
  Lori Farkash

- **Earth and Space Sciences**

  Introduction: *Understanding Our Planet* 211
  Brian Vorwald

  Water Use and Misuse: A 5E Mini-Unit 213
  Annie Madden

  Metric Measurement, Models, and Moon Matters: A 5E Mini-Unit 227
  Thomas O'Brien

MOVING FORWARD 242
Alan J. McCormack

Chapter 7

Science? Literacy? Synergy![1]

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In the introductory chapter of his career-crowning work, *Consilience: The Unity of Knowledge*, eminent biologist E.O. Wilson describes an incident that transformed his intellectual world and fundamentally reshaped his understanding of natural science. A new university student chattering enthusiastically about the ants of Alabama to an assistant professor at Cornell University, Wilson was suddenly thrust a copy of Ernst Mayr's 1942 *Systematics and the Origin of Species*. "Read it," said his mentor, "if you want to become a real biologist."

This thin volume united Darwinian theory and modern genetics and gave an expanded theoretical structure to natural history. Wilson continues, "A tumbler fell somewhere in my mind, and a door opened to a new world." The role that reading played in Wilson's subsequent development is not the topic of his book, but this anecdote dramatizes the point we want to make in this chapter regarding the role of literacy in the work of learning and practicing science: that reading and writing are integral to the work of science. While it is probably perilous to draw too many parallels between the science practiced by professionals and science learning in elementary classrooms, the connection we propose is modest: we suggest that reading and writing are integral to the work of learning and practicing science at every level. Thus, if educators are serious about developing strong understandings of science for all learners, whether or not students intend to become professional scientists, then reading and writing science should also be viewed as supporting rather than supplanting the development of knowledge and inquiry in science from the earliest years of schooling.

What is the "Literacy" in Scientific Literacy?

Scientific literacy has been the rallying cry for science education reform for the last twenty years, as many different groups have sought to enhance science learning for all children and youth. Yet this

1 This chapter is based in part on Pearson, Moje, and Greenleaf 2010.

phrase has had multiple, and sometimes conflicting, meanings. Does the literacy in scientific literacy refer to a general facility with science concepts needed to understand science for everyday life? Does the "literacy" in "scientific literacy" have anything to do with the reading and writing of science texts? Is literacy as reading and writing even an aspect of scientific inquiry? Or does "scientific literacy" refer to the ability to think and practice like a professional scientist? Equally important, why does scientific literacy in any of these senses matter?

The professional literature reveals multiple ways of thinking about scientific literacy, but at least two conceptualizations dominate. The first focuses on general familiarity with the workings of the natural world and with key science concepts, principles, and ways of thinking (Rutherford and Ahlgren 1990). This perspective on scientific literacy is what Norris and Phillips (2002) refer to as a definition of scientific literacy based on a *derived* sense of literacy, as captured here by Rutherford and Ahlgren in the introduction to the 1990 American Association for the Advancement of Science Benchmarks:

> [Scientific literacy involves] *being familiar with the natural world* and respect for its unity; being aware of some of the important ways in which mathematics, technology, and the sciences depend upon one another; *understanding some of the key concepts and principles of science; having a capacity for scientific ways of thinking*; knowing that science, mathematics, and technology are human enterprises, and knowing what that implies about their strengths and limitations; and being able to use scientific knowledge and ways of thinking for personal social purposes. (Rutherford and Ahlgren 1990, x. italics added)

What is noteworthy about this view of scientific literacy is that nowhere in the definition is the reading or writing of print texts —or any other texts—mentioned. The importance of having facility with texts *is* discussed in the Benchmarks, to be sure, but when defining scientific literacy, the focus is generally on useable science knowledge for active participation in the world.

The second dominant perspective on scientific literacy makes an explicit connection between the language of science, how science concepts are rendered in various text forms, and access to both science knowledge and participation (Norris and Phillips 2002). This conceptualization is what Norris and Phillips refer to as the *fundamental* sense of science literacy:

> If scientific literacy is conceived only as knowledge of the substantive content of science, there is a risk that striving to learn the elements of that content will define our goals without any appreciation *for the interconnection among the elements of content, their sources, and their implications* . . . .When it is also recognized that *science is in part constituted by text and the resources that text makes available*, and that the primary access to scientific knowledge is through the reading of texts, then it is easy to see that *in learning how to read such texts a great*

deal will be learned about both substantive science content and the epistemology of science. (Norris and Phillips 2002, 236-237. Italics added)

Here in these quotes, we see—particularly in the italicized sections—that the emphasis is on how science knowledge is constituted by the tools used to communicate that knowledge. Researchers and teachers guided by the more "fundamental" view of scientific literacy are concerned not only with how students develop the proficiencies needed to engage in science inquiry and acquire science understandings, but also the role of representation (in words, arguments, texts, and images) in coming to understand and practice science. That is, they are concerned with how students develop the abilities necessary to access and produce science knowledge by reading, writing, and reasoning with the language and texts.

In this chapter, we focus on the fundamental view of scientific literacy. As such, we will suggest that the ability to make meaning of oral, written, and visual language representations is central to robust science knowledge, to participation in scientific inquiry, and to meaningful engagement in public discourse about science (Yore 2009). We will further argue that, when students learn how to read and write about science, they also learn about the substantive, epistemological, and methodological bases of science. We will push against the false dichotomy between scientific literacy and science inquiry: If science literacy is conceptualized as itself a form of literacy and if literate practices are used to advance scientific inquiry, rather than as a substitute for inquiry, attempts to extricate literacy from inquiry are counterproductive for students. And, we will argue that scientific literacy in the fundamental sense should be a focus of instruction from the earliest years of schooling.

Changing Views of Literacy and Science

The division between the derived and fundamental perspectives on scientific literacy as it is manifest in school instruction can be traced to an historical division between text-based science instruction and inquiry-based science instruction that arose in the middle of the last century. Although John Dewey and others had advocated the teaching of inquiry in science education as early as 1910, those designing school science programs emphasized textbook-driven instruction and focused on the products of science—scientific knowledge—rather than the process of science—at least until a half-century later, when Sputnik came along in 1957. Following the Soviet Union's coup, the National Science Foundation (NSF) took an interest in reforming science education to better prepare students for careers in science. The NSF began to fund professional development and curriculum development efforts that positioned inquiry as an essential part of the content of science instruction and as an essential means of developing scientific understanding and scientific habits of mind (Bybee 1997; Rutherford 1964).

The best of intentions aside, the NSF-funded curriculum efforts of the 1960s underestimated the magnitude of the change required to transform the dominant, incredibly resistant textbook-driven

science curriculum into inquiry-driven, firsthand science. Implementing inquiry-based science brought with it many challenges, foremost the lack of teacher knowledge and experience with inquiry and its pedagogical entailments, but including materials management, time, and orchestrating activity (Anderson 2002; Bybee 1997). Further, the 1960s inquiry-based science curricula were more focused on teaching than on learning and thus did not anticipate the need for teachers to modify instruction according to the prior knowledge and responses of students (Duschl, Schweingruber, and Shouse 2007). By the 1980s, many schools and school districts had returned to textbook-driven teaching practices (Weiss et al. 2003). In the decades that followed, two divergent approaches to science education came to dominate—mainly-textbook-based and mainly-experience-based science instruction. Textbook science programs included few firsthand experiences for students, focusing instead on the use of reading textbooks and completing textbook and/or worksheet problems. Inquiry-based science programs supported by the National Science Foundation included little reading or writing, focusing instead on firsthand experiences with materials and models.

Current research on science learning demonstrates that students learn best through a combination of firsthand experience and ample opportunities for reflection and rich talk about their work. This combination allows students to connect new information to what they already know, increasing the likelihood that they will learn and remember it (Bransford, Brown and Cocking 2000; Brown and Campione 1994; Metz 2000; National Research Council 2000). In addition, conceptions of proficiency in science are expanding to include dispositions and practices of science beyond factual knowledge and inquiry skills. The recent National Research Council brought together a Committee on Science Learning, Kindergarten through Eighth Grade, composed of experts in cognitive and developmental psychology, educational policy and implementation, classroom-based science education research, the natural sciences, the practice of science teaching, and science learning in informal environments. Together, they produced a report called *Taking Science to School* (Duschl et al. 2007), which set a new bar for students' science proficiency. It calls for students to: (a) know, use, and interpret scientific explanations of the natural world; (b) generate and evaluate scientific evidence and explanations; (c) understand the nature and development of scientific knowledge; and (d) participate productively in scientific practices and discourse.

The expanded conceptualization of science proficiency has been associated with the fundamental view of scientific literacy, in which reading and writing are seen as necessary tools for achieving this expanded skill set (see, for example, Yore and Treagust 2006; Yore et al. 2004). In addition, whereas the 1990 Science Benchmarks described earlier largely defined scientific literacy in terms of possessing scientific knowledge about the natural world (National Research Council 1990), more recent standards and policy documents in science have attended more to the role of reading and writing in scientific literacy. The National Research Council's (2011) new framework for science education is even more explicit about the role of reading and writing as fundamental to the practice of science and engineering.

Literacy as Tool for Scientific Inquiry

One key to navigating the historical divide between textbook and inquiry science is the appropriate positioning of reading and writing as tools for engaging in science inquiry, rather than as ends unto themselves. In a comprehensive survey about elementary science instruction, less than half the teachers reported that learning inquiry skills was a major objective of their classroom instruction and only about half of the teachers reported engaging students in firsthand experiences on a weekly basis (Fulp 2002). It is this kind of inattention to inquiry at the elementary level that has made inquiry-based science educators wary of increasing attention to reading and writing of texts in science. However, it is possible to use literacy instruction and activities in ways that increase and deepen students' involvement in inquiry. Literacy activity and instruction in science should engage children and youth in making sense of scientific texts in the service of inquiry informed by the ways that scientists' use reading and writing to inquire about natural phenomena. Although scientists often engage in unstructured explorations of the natural world, formal investigations are always framed by other investigations. No scientist simply walks into a lab and starts manipulating materials, tools, and phenomena. Scientists situate their work in that of other scientists, and they learn about the work of others largely through reading. Texts are the artifacts of past investigations and are used for inductive reasoning about scientific phenomena. Scientists use texts to generate questions that advance the design and enactment of new lines of investigation or to provide the background necessary for replication. Most scientists also write regularly to keep track of their investigations and, later, to go public with their work.

In light of the centrality of reading and writing to the work of inquiring in science, it is clear that the attempt to protect inquiry-based science from the incursion of text is both inauthentic and unproductive. Science instruction can engage children and youth in making sense of and producing scientific texts as an integral part of scientific inquiries. Both firsthand experiences and text-based work can be viewed as part of investigations when they are positioned as methods of answering meaningful scientific questions. In such contexts, literate practice is not simply the passive receipt of information about science, but rather a process of actively making meaning of science. When science literacy is conceptualized as a set of tools for inquiry and situated in the context of ongoing investigations, children and youth can engage in authentic disciplinary practices such as:

- Reading to find out what other scientists know about a topic in order to formulate questions for investigation;
- Reading to find evidence to support and/or refute their own or others' explanations with data;
- Reading to learn about methods of inquiry that they can use in their own investigations;
- Reading to gather information that can inform their investigations along the way;
- Writing to document their methods, observations, and results;

- Reading to follow curiosities that may someday lead to more formal investigations;
- Reading to learn about how scientists think about the natural world, how they shape inquiries, and how they interpret evidence;
- Writing to make sense of their results and wrestle with complicated ideas;
- Engaging in discussions with colleagues (classmates) to plan and make sense of their investigations;
- Writing to communicate their findings and connect their investigations to a wider world of scientific phenomena, knowledge, and research;
- Engaging with public discourses on topics that concern science;
- Reading and writing to imagine science identities and lives; and
- Reading and writing as part of inquiries that address problems in their communities that concern science.

We want to emphasize that although reading is often privileged over writing in discussions of scientific literacy, constructing texts is as important as understanding them. Writing plays a critical role in documenting investigations, and it is a critical tool of sense-making and communication. Curwen, Miller, White-Smith, and Calfee (2010) report on a professional development program designed to help teachers use the Read-Write Cycle to develop students' metacognition in science. Teachers engaged third through fifth grade students in learning about and using a variety of reading comprehension strategies in their science and in using graphic representation and writing to organize their ideas about the content after reading. The students also used writing to synthesize and reorganize their knowledge over time. Teachers involved in a design experiment reported that students who participated in the project became more deliberate and conscious as they approached the cognitive demands of content area texts and were better able to build conceptual generalizations across texts.

In addition to supporting the development of science understandings within and across texts and firsthand experiences, producing one's own representations (e.g., in notebooks, diagrams, charts, and reports for others to read) helps students understand how and why scientists think and write the way they do (Miller and Calfee 2004). For example, in work with middle and high school youth in Detroit (Moje et al. 2004), teachers regularly ask students to evaluate whether their written representations refer back to the hypotheses they made, whether they made the data evident, and whether they have provided valid reasoning to support their claims. When students have to defend their claims to one another, they begin to recognize the value of clear and explicit representations of what they found (Osborne 2010).

Science as a Site for Enhancing Literacy

The most important reason to engage with a more fundamental perspective on scientific literacy is that it is a better reflection of scientific practice than either the memorization of scientific facts or firsthand inquiry alone. It is also important to note, however, that such a view also represents a significant advance for literacy learning. Just as literacy tools and artifacts can enhance the acquisition of knowledge and inquiry in science, so too can science provide an ideal context for acquiring and refining literacy tools.

For decades reading instruction was grounded in a "generalist notion of reading" (Shanahan and Shanahan 2008, 41). In a generalist view, reading is understood as a set of skills that can be applied to different texts for different purposes. The implicit assumption in this view is that students who are taught to read texts (mainly narratives) they encounter in basal readers will later fluidly transfer their reading skills to content-area texts. This view has been called into question—particularly in recent years—by reading educators who, motivated in part by a robust body of research that indicates that reading comprehension is shaped by literacy experiences with particular text genres, disciplines, and discourses, have expressed concern that the emphasis on fictional literature to the exclusion of nonfiction text genres has failed to prepare students for the texts and tests of later schooling (Alvermann 1991; Alvermann, Moore, and Conley 1987; Herber 1978; Rand Reading Study Group 2002; Santa and Alvermann 1991). Those who study the use of informational text have argued that the balance of texts in early reading should better reflect the balance of texts that students will encounter in later grades and in their lives outside of school—contexts dominated by nonfiction text genres (e.g., Duke and Bennett-Armistead 2003).

Several recent reports on reading and adolescent literacy have also called this generalist view of reading into question, arguing for more attention to text- and discipline-specific reading practices (e.g., Alliance for Excellent Education 2010; Heller and Greenleaf 2007; Rand Reading Study Group 2002). These reports point to the need not only to get started early with discipline-specific reading and writing, but also to continue to support students' development of literacy skills beyond the early elementary years. The emphasis here is not simply about helping students decode or comprehend content-area textbooks; it is about supporting students in learning to read and write in ways that will specifically foster involvement in disciplinary learning (Carnegie Council on Advancing Adolescent Literacy 2010; Common Core State Standards 2010; Lee and Spratley 2010).

Several scholars (e.g., Duke 2000; Moje 2007; Schoenbach and Greenleaf 2009; Shanahan and Shanahan 2008) have argued that without systematic attention to reading and writing within subjects like science and history, students will leave schools with an impoverished sense of what it means to use the tools of literacy for learning or even to reason within various disciplines. Science provides a setting in which students are intellectually obligated to draw inferences, construct arguments based on evidence, infer

word meanings, construct meaning from text, and use their reading and writing from within and across texts to make sense of observations in the world —the very skills required as good readers and writers. Students fine-tune their literacy tools not only when they read and write science texts but also when they engage in science investigations precisely because so many of the sense-making tools of science are consistent with, if not identical to, those of literacy (Goldman and Bisanz 2002).

In spite of the many calls to begin instruction with disciplinary literacies in the elementary years, there are some significant obstacles. Perhaps the most significant obstacle to the development of scientific literacy in the early years of schooling is the scarcity of any form of science teaching at the elementary level. Elementary students too often are excluded from developing scientific literacy in *either* the derived or fundamental senses. The status of science teaching in elementary classrooms has been severely influenced by the zeal with which the No Child Left Behind (NCLB) initiative promoted reading and math over science and other subjects, leaving precious little time for science (McMurrer 2008; Tugel 2004). This has changed the landscape of the school day, prompting some educators to suggest that elementary science has fallen into a "quiet crisis" (Feller 2004; Toppo 2003). Even before changes to elementary classrooms prompted in part by No Child Left Behind (NCLB) legislation, elementary teachers devoted an average of less than two hours per week of instructional time to science (Fulp 2002). And, there were indications that time devoted to science was declining. In a large-scale survey study of the impact of NCLB on elementary classroom instruction, 29% of the districts surveyed reported that they had reduced instructional time devoted to science in order to allocate more time to reading and mathematics (Rentner et al 2006). A 2008 national survey revealed that a majority of elementary schools decreased the time allotted to science by 15 minutes per day whereas time for reading and math was increased by a like amount (McMurrer 2008). In a recent study of teachers in Northern California, Dorph, Goldstein, Lee, Lepori, Schneider, and Venkatesan (2007) found that 80% of the 923 elementary teachers surveyed reported that they spent less than one hour per week teaching science.

The renewed emphasis on language arts and mathematics and the onset of yearly, multiple-choice testing in those subject areas make it difficult for schools to promote science teaching at all, much less inquiry-based teaching. The science assessments that have been added to the state assessment batteries at the elementary level, like the literacy assessments before them, are multiple-choice tests that privilege the assessment of facts over concepts or knowledge frameworks. The combination of high stakes (rewards and sanctions based on performance) and low intellectual challenge (the factual character of the vast majority of test items) will compel teachers to eschew deep inquiry in favor of content coverage (Weiss et al. 2003). As a result, the status of science instruction at the elementary level should be a major concern for all literacy and science educators. If we want to make progress toward the goal of scientific literacy for college, career, and citizenship, we need to start earlier, when students' curiosities about the natural world are first ignited.

Getting Started Early

While there are still many impediments to increasing attention to literacy in middle and high school science classrooms, secondary science initiatives are beginning to attend to fundamental scientific literacy development for adolescents. Recent policy initiatives have supported interventions for struggling reading and efforts to develop the ability of secondary teachers to support students' literacy development (Moje 2008). However, few science educators, literacy researchers, policy makers, or practitioners are attending to the development of fundamental scientific literacy for elementary students, though there is ample evidence that they should.

In this section, we will describe several programs of instruction that enable students to get started early in school with scientific literacy. We will focus mainly on the instructional routines employed in each, though it is important to note that all of these programs come with the virtue of having experimental evidence of their efficacy in supporting students' learning in both literacy and science. The instructional programs described below share key ingredients: they are embedded in inquiry-based science instruction and are driven by significant questions about the natural world; they engage learners in using text and firsthand experiences to answer these questions; and they provide explicit instruction in the reading and/or writing of science texts in the context of these investigations.

Concept-Oriented Reading Instruction (CORI)

For more than 20 years, Guthrie and colleagues have been refining and studying CORI, an elementary-level program designed to promote a number of literacy goals through the use of broad interdisciplinary themes (Guthrie and Ozgungor 2002), primarily drawn from science curricula, such as exploring the impact of humans on animal habitats. CORI instruction begins with content knowledge goals within a conceptual theme. Firsthand experiences related to the theme are typically used to generate interest in the topic. Students generate questions about the theme and use reading and firsthand investigations to answer their questions. As students engage in these investigations, CORI teachers provide explicit instruction in reading strategies, such as questioning, activating background knowledge, searching for information, summarizing, and synthesizing information in order to communicate with others. One goal of the CORI program is for students to experience how the information they obtain from firsthand activities and the information they acquire from reading can work together to deepen their understanding of a science topic (Guthrie 2001; Wigfield et al. 2004). For example, during a unit about how animals survive in different environments, CORI students dissect owl pellets to learn what owls eat. As they do this, the teacher encourages them to ask questions about owls and other birds. The students record their questions in their science journals, and seek out books to help answer the questions. As students engage with the texts, the teacher explains how the features of informational books—such as indices and headings—can help them find answers to their questions. The teacher guides students to understand the organization of the text at the paragraph level, as well, explaining that paragraphs in

informational texts often begin with a general principle and then provide details and examples. Students share their questions and answers as a class, and the teacher helps the students form links back to the theme of survival in different environments.

Of particular interest in the CORI program is the pivotal role of motivation supports, such as student choice (about tasks and texts) and collaboration (sharing questions, texts, and information), in advancing students' learning in both science and literacy. CORI has been shown to increase students' concept learning in science, their reading motivation, their use of productive inquiry strategies, and their overall text comprehension compared to control classrooms with separate science and literacy instruction (Guthrie et al. 2004).

Guided Inquiry Supporting Multiple Literacies (GIsML)

Palincsar and Magnusson (2001) engaged in a multi-year program of research on the ways that hands-on (firsthand) experiences and text-based (secondhand) experiences can together support students' conceptual understandings and scientific reasoning. In GIsML professional development, elementary teachers learn to engage students in cycles of investigation guided by specific conceptual questions, establishing the classroom as a community of inquiry. GIsML emphasizes sustained involvement in investigations of significant questions in science—e.g., What influences the motion of a ball down a ramp? How does light interact with objects? What changes make sounds different? (Palincsar and Magnusson 2002a, 2002b, 2002c). Within an investigation, students engage in an inquiry sequence in which they prepare to investigate, collect, and analyze data, prepare to report their findings, and report (Hapgood, Magnusson, and Palincsar 2004). The investigations combine firsthand explorations of the natural world with secondhand experiences through the use of a fictional working scientist's notebooks. The notebook texts, which include exposition, narration, and representations of data, are a kind of "think-aloud" by a scientist as she engages in her own investigation of the guiding questions (Hapgood, Magnusson, and Palincsar 2004). After students investigate scientific questions firsthand, they consult text to learn how the scientist has interpreted similar evidence. The notebooks engage students in interpreting data along with the scientist and inform students' answers to the guiding questions by adding confirming evidence, new ideas, and, sometimes, contradictory evidence that students must reconcile with their own observations. Students use discussion and further investigation to make sense of similarities and differences. The texts also model a scientist using secondhand materials, reading and interpreting with a critical stance, and drawing conclusions from multiple sources of evidence. The notebook texts provide many opportunities to engage with different kinds of representations of data, such as tables and diagrams. In one GIsML unit described by Hapgood et al., second graders investigated factors that influence the motion of an object on an inclined plane. In this unit, the scientist's notebook text took the form of a big book. The book described how the fictional scientist, Lesley Park, came to wonder about motion through her experiences in the world and how she followed up her wonderings with investigations using ramps and balls. The students were encouraged to engage

with the text in a highly interactive manner, making predictions and claims, critiquing the scientist's reasoning, and using Lesley's tests as a model for their own firsthand investigations. Over the course of the unit, which involved the reading of two scientists' notebooks and engaging in several firsthand experiences, students developed important skills of scientific literacy, including interpreting firsthand and secondhand data and leveraging those data as evidence and making sense of multiple forms of representation. In a separate quasi-experiment comparing fourth graders studying light in either a GIsML or a "considerate text" (i.e., especially well-written, cohesive text) treatment, GIsML researchers found that students learned more in the GIsML instruction than in the considerate text condition, concluding that the notebooks promoted talk that led to greater engagement and, ultimately, improved understanding (Palincsar and Magnusson 2001).

In-depth Expanded Applications of Science (Science IDEAS)

Romance and Vitale (1992, 2001) developed the IDEAS model of integrated science/language instruction for elementary students, which replaces the time allocated for traditional literacy instruction with a 2-hour block of science that includes literacy skills. The science instruction is concept-focused and involves firsthand experiences, attention to science process skills, discussion, reading comprehension, concept mapping, and journal writing. Particularly notable in the Science IDEAS model is the planning process that teachers use to create IDEAS units. The teacher begins by creating a concept map around a core science concept, such as evaporation. Often, the teacher will write ideas related to the key concept on sticky notes and move them around until they form a network of related ideas. The resulting concept map serves as the blueprint for the design of the unit. The teacher uses the concept maps to plan instructional experiences, taking into account what the students know and how the concepts connect to students' everyday experiences. IDEAS teachers annotate the concept map with ideas for firsthand investigation, writing opportunities, and reading opportunities—all in the interest of building students' conceptual understanding. For example, in an evaporation unit, students might learn that heat is a factor in speeding up evaporation by observing that a wet paper towel placed near a heat source will dry more quickly than a paper towel placed away from the heat. The students might write in their journals throughout the unit, documenting the results of their firsthand investigations and explaining how each of the firsthand experiments helped them understand something new about evaporation. Students might read a text to learn more about the process of evaporation at the molecular level, engaging in a careful sentence-by-sentence discussion of the ideas and of how the text communicates those ideas. The students might reorganize ideas from text using manipulable concept maps. In doing so, they come to better understand both the organization of the concepts and the ways that concepts are encoded—and can be decoded—in science text. Several multi-year efforts with students in grades one through five show that Science IDEAS students outperform students receiving segregated language arts and science instruction on standardized reading and science tests.

Seeds of Science/Roots of Reading (Seeds/Roots)

Seeds/Roots (see Cervetti et al. 2006) began as an attempt to embed inquiry-oriented reading, writing, and language activities within the already successful GEMS (Great Explorations in Math and Science) K-8 inquiry-based science program. The program is based on the fundamental principle that reading, writing, and discourse are best enacted in science as tools of inquiry. Students use firsthand experiences, reading, writing, and discussion to answer meaningful science questions. For example, in one unit about light for third and fourth graders, students investigate the question, "How does light interact with different materials?" by

- investigating with flashlights and materials;
- using their growing knowledge of text features to search a reference book with data on light's interactions with other materials;
- recording their evidence from both firsthand and text sources; and
- engaging in discussions about their evidence.

As they engage in this investigation, they also read a book about why communication among scientists in general and disagreement in particular are important for moving science ahead. In another unit, students conduct an inquiry into the best ingredients to use in designing a mixture that will serve as glue. As they conduct their hands-on investigation, they read a book entitled *Jess Makes Hair Gel*, in which the protagonist demonstrates stamina and persistence in trying to find the right set of ingredients to make hair gel to control his unruly hair. The lesson they take away from the reading (you have to be systematic and persistent when you are engaged in design research) applies directly to their ongoing glue-making investigation. They also encounter "models" of how to record their ongoing methods and observations; those skills will prove useful in completing their unit assignment.

Across two experiments comparing Seeds/Roots with a content-controlled inquiry science comparison group, the curriculum-based Seeds/Roots program demonstrated advantages on measures of science understanding and vocabulary acquisition, with a less consistent advantage for reading comprehension for students in grades 2-4 (Cervetti et al. in press; Wang and Herman 2005). In the more recent of these studies, fourth-grade students using the Seeds/Roots curriculum also made significantly greater gains in their science writing than did students in a control condition.

Lessons from Adolescent Programs

It is no secret that much more work has been completed on issues of integration in middle and high schools than in elementary, if for no other reason than there is much more science curriculum and pedagogy available in those settings. And there are lessons to be learned--or at least hypotheses to be tested empirically--for those of us in elementary science and literacy. For example, Greenleaf and colleagues at the Strategic Literacy Initiative at WestEd have been developing models of discipline-based

literacy instruction and professional development (under the rubric of Reading Apprenticeship) to foster more engaged academic learning for underprepared students in secondary and post-secondary settings (Greenleaf, Brown, and Litman 2004). In this apprenticeship model, science teachers inquire deeply into what they do as readers and thinkers to derive meaning with complex science texts of varied kinds—including science explanation and exposition in scholarly journals as well as the diagrams, data arrays, mathematical expressions, and graphs that convey information. Teachers then learn classroom routines for engaging students in active inquiry and sense-making with such texts: routines for modeling and mentoring students in productive reasoning processes; fostering metacognitive awareness of comprehension problems and problem-solving processes; and for promoting collaborative discussions of science texts. A second example of an adolescent program that can inform fundamental scientific literacy instruction at the elementary level is the work of Moje and her colleagues with middle and high school youth in Detroit (Moje et al. 2004; Sutherland et al. 2006; Sutherland et al. 2006; Textual Tools Study Group 2006). Teachers involved in the project engage students in reading both scientific and lay-audience texts related to phenomena under study. The teachers also engage students in translating across multiple forms of representation, particularly as they gather data and formulate explanations to communicate their findings. When writing explanations from scientific investigations, students engage in peer review to evaluate whether their written explanations refer back to the hypotheses they made, to what extent they made the data evident, and the quality of reasoning they have provided for their claims. Writing in this way supports students in developing stronger science conceptual knowledge and better scientific explanations.

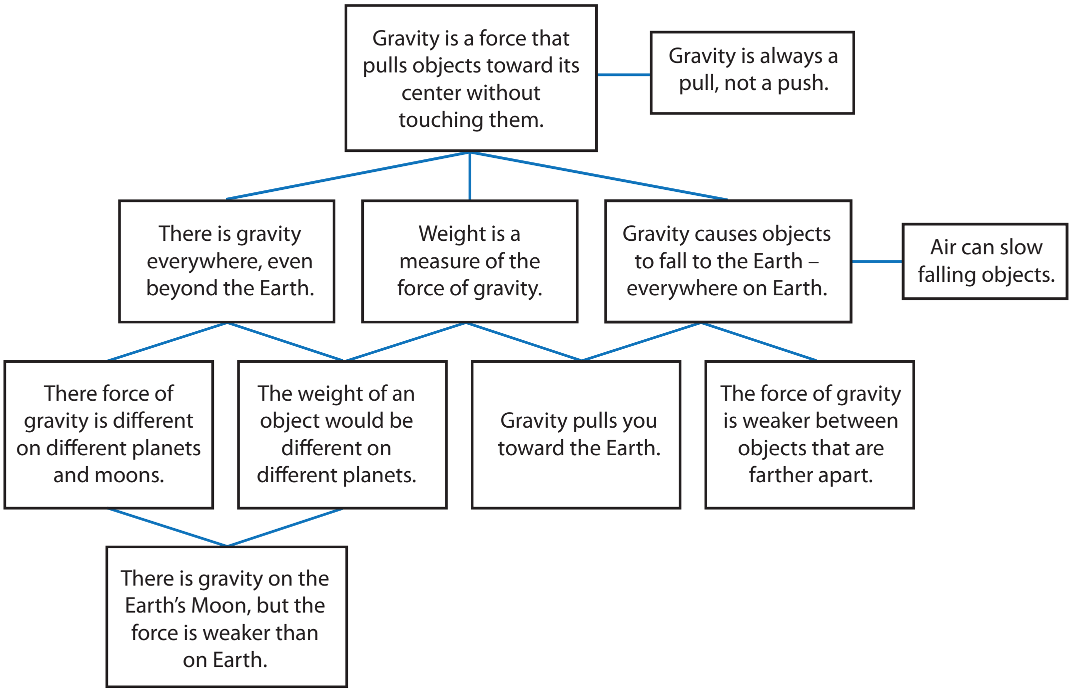
Summary

This body of evidence demonstrates the promise of approaches to literacy and science instruction that are integrated in the service of inquiry, showing that it is possible to improve the instructional quality of both science and literacy teaching and learning. We are encouraged by the fact that other groups have found similar results (e.g., Anderson et al. 1997; Calfee and Miller 2004; Gomez and Gomez 2007; Pappas et al. 2002) documenting the efficacy of text and literacy activity within science curricula.

Planning Instruction that Supports Fundamental Scientific Literacy

Increasingly, there are published curricula designed to support elementary students' development of scientific literacy. However, it is also possible to get started without the support of a comprehensive integrated curriculum. In this section, we outline a planning process that you might use to infuse an existing inquiry-based program with opportunities for scientific literacy development, using examples from a gravity unit.

1. Begin by mapping the inquiry-based science unit's goals and inquiry experiences in a list or a concept map. A map for a week-long unit on gravity might look something like this:



2. Look through the unit's inquiry experiences and associate each with concepts in the map. For example, in order to understand how weight and gravity are related, the unit might follow a period of open exploration with an activity in which students investigate the question, "Is there gravity on the moon?" by engaging in activities such as weighing different objects and using an Internet-based calculator to figure out how much these same objects would weigh on the moon. Try to ensure that every concept on the map is associated with firsthand experiences and that students have several opportunities with more extended inquiries in which they pose a question, gather evidence, and make sense of the evidence. You may wish to use web resources to augment your unit. NASA offers many resources for teachers and students, including the following sites:
   - http://www.nasa.gov/audience/foreducators/topnav/materials/listbytype/Gravity on Earth Versus. Html
   - http://www.nasa.gov/audience/forstudents/k-4/stories/what-is-microgravity-k4.html
   - http://www.nasa.gov/audience/foreducators/topnav/materials/listbytype/Why Do Astronauts Float Inside.html
   - http://www.nasa.gov/audience/foreducators/topnav/materials/listbytype/The Constant Pull of Gravity.html
   - http://www.nasa.gov/audience/foreducators/microgravity/home/toys-in-space.html
3. Review your grade-level science standards and augment the unit's goals so that it includes attention to science concepts, science inquiry skills, and understandings about the nature of science. For

example, the gravity unit might include goals such as observing and formulating questions based on observations, comparing and contrasting, and understanding that science knowledge is based on evidence. Identify opportunities in the unit to develop each of these skills and understandings. For example, as students read and engage in firsthand investigations, recor" evidence for key questions, such as "Does gravity pull on all objects with the same force?" on chart paper. Point out to students that scientists also gather evidence from different sources to answer important questions and build scientific knowledge.

4. Next, ask yourself, "How might reading and writing be used in ways that support students' involvement in this unit?" For example, students might benefit from reading about how scientists set up fair tests and observe systematically over time. Their investigations may also be enhanced by attention to writing about observations and augmenting observations with illustrations. If you think your students will struggle with the concept of gravity as an invisible force, they may benefit from the explanations and images that a trade text like *Gravity is a Mystery* by Branley and Miller offer. Make a list of these potential opportunities.

5. Look through your English language arts standards for learning goals that support your work in the unit. For example, the English language arts standards from the Common Core State Standards include many goals that can be supported through integration with an inquiry-based science unit, including goals related to integrating information gained from reading two or more texts, taking notes,; organizing information; and writing explanations. You might also include goals related to students' use of informational text features, such as headings, glossaries, and images. Look through your unit map with an eye to opportunities to infuse reading, writing, and talking. Add these experiences to your unit map.

6. Begin to identify science trade texts that fit with the themes of the unit. Look for texts that provide insight into the dispositions and processes of science (e.g., scientist biographies and discover narratives), as well as books that explain and illustrate science concepts. The following articles offer lists of excellent science trade books on a wide variety of topics:

    - Bircher, L.S. (2009). Reading aloud: A springboard to inquiry. *Science Teacher*, 76(5), 29-33.
    - Brassell, D. (2006). Inspiring young scientists with great books. *Reading Teacher*, 60(4), 336-342.
    - Morrison, J.A., and Young, T.A. (2008). Using science trade books to support inquiry in the elementary classroom. *Childhood Education*, 84(4), 204.

7. Read an reflect on what you do to make sense of the reading materials you collect. Think about how you can model and mentor students in these same reading and reasoning processes. How can you

share strategies for recording observations, overcoming the obstacle of unknown words in texts, or quickly determining whether a text will help answer a particular question?

8 Develop assessments that will help you track students' progress toward the unit's goals.

Moving Forward

The path toward greater proficiency in science reading, writing, and inquiry for all students will necessarily travel through the classrooms of knowledgeable teachers who understand the vital role literacy plays in enhancing rather than replacing science learning and who can mentor their students in these practices. Teacher knowledge is the key to advancing student achievement. A number of programs are changing the ways that teachers are prepared and changing the instructional materials that are available to practicing teachers to invite stronger attention to language and literacy in science. Many of the efforts we describe in this section are situated in secondary education, but the insights gained from these programs are applicable to teachers across the K-12 spectrum.

Initial Teacher Preparation

Initial teacher preparation has often virtually guaranteed isolation between literacy and science instruction by teaching literacy methods and science methods separately. Moje and colleagues (Bain and Moje 2012; Moje and Bain 2011) have redesigned the secondary teacher education program at the University of Michigan to focus on building new teachers' understanding of the disciplinary practices supported by reading, writing, and reasoning, rather than treating literacy methods as a separate subject for teachers preparing to teach science or any other secondary school discipline. This redesign has afforded the opportunity for teaching interns to examine the texts of science, to plan instruction that integrates complex uses of text into inquiry, and to learn how to teach young people how to think, read, and write like scientists so that they can either pursue additional science training or act as responsible citizens in a world shaped by scientific decisions. Persuaded by the argument that such attention to the role of language and literacy in the disciplines should begin at the earliest levels of instruction, the university also recently funded the hiring of a cluster of elementary-level subject-area scholars who specialize in literacy instruction integrated into science and social studies.

Other projects to reconceive the approach to literacy instruction in teacher preparation programs are noteworthy. For example, Donahue (2003) and Braunger, Donahue, Evans, and Galguera (2004) describe a discipline-centered approach to courses for literacy methods, required for secondary teaching credentials. In dramatic contrast to traditional teacher preparation courses that maintain separate offerings for science and literacy teaching methods and offer literacy methods as a set of instructional strategies to help students access science content from texts, in these programs, literacy is promoted as a tool for active, inquiry-based science learning that can support students in acquiring

science understandings and reasoning processes and a deeper appreciation for the nature of science investigation and knowledge.

Ongoing Professional Development

Because teaching is a professional enterprise, teachers continue to develop knowledge and craft of the profession as they teach, in part through their association with science colleagues or professional organizations, and in part through professional learning opportunities such as seminars and institutes. Although professional offerings available to learn new science content and approaches to inquiry abound, opportunities to learn to support students' development of science reading and writing skills and strategies are slim. Greenleaf and colleagues (e.g., Greenleaf and Schoenbach 2004) offer a model of what such professional development opportunities might look like. They have developed programs specifically designed to support teachers in developing more robust conceptions of science reading and its role in learning.

Merely teaching science teachers a collection of literacy strategies does not help and may actually hurt. Instead, teaching literacy in scientifically specific ways requires conceptual change for teachers. The challenge facing professional developers is to help teachers move to new ways of thinking and acting in the classroom to promote deep thinking and reasoning around texts and investigations and to learn to implement instructional routines that support scientific reasoning no matter the data of classroom reasoning – text or phenomenon or investigation.

Promoting deep thinking and reasoning among teachers (and their students) is facilitated when professional development appropriates inquiry processes, making the literacy/science connection and reasoning processes of inquiry themselves the object of ongoing professional inquiry. Central questions driving these professional inquiries for teachers include:

- For what purposes do scientists read and write?
- What counts as text in science?
- What do we know and do as skillful readers and writers of scientific texts?
- How can we make this knowledge and these processes apparent to our students?
- How can we provide students with opportunities to practice and the mentoring and guidance they need to acquire these vital science literacy proficiencies?

By taking an inquiry stance as they investigate their own science literacy practices, teachers can simultaneously develop the insights and pedagogical moves they will need to mentor their students. A recent study affirms that these kinds of carefully designed learning opportunities for teachers can and do translate into increased achievement for students (Greenleaf et al. 2011).

One common misconception secondary science teachers hold about reading originates in the "expert blind spot" phenomena. Because these teachers are themselves disciplinary experts, instructional texts meant for students hold no mysteries or challenges for them. The ease with which science teachers are able to comprehend traditional science textbooks blinds them to the difficulties students may have. But when such teachers have an opportunity to dig into science writing that poses challenges for them, they begin to see that reading complex science text is neither automatic nor straightforward. Challenging texts require even knowledgeable science readers to put into play their many skillful problem-solving strategies, to marshal stamina and effort for the undertaking, and to maintain a high level of self-motivation to stay with the task in order to gain new understandings (their first love). Teachers emerge from such engagements with new eyes for the challenges their students face with science texts, as well as a deeper appreciation of their own capabilities as science readers, capabilities they realize they can help their students gain. Teachers who undergo this experience as temporarily "disabled" also begin to recognize how poorly many of our textbooks represent authentic reading and writing about science (Schoenbach and Greenleaf 2009) and how difficult it would be for their English language arts colleagues to assume responsibility for mentoring and engaging students in the rigors and rewards of science reading. As developers of such programs of teacher preparation, Greenleaf and her colleagues have found that science teachers who are inquiry oriented can take up the text as another data source to investigate the natural world. Conversely, for science teachers who are text oriented, learning to carry out text investigations becomes a way into science reasoning and inquiry. Integrating science and literacy can thus be a back door into inquiry approaches for teachers who are not already inquiry-based science teachers. Such opportunities to investigate science literacy practices need to be made available to teachers on a broad scale.

Curriculum Development

In the past thirty years, policy makers, practitioners, and researchers have launched many inspired efforts to fundamentally reform K-12 science education with a focus on investigation and inquiry in keeping with the nature of science knowledge and activity. However, in these efforts, the quality of and role of reading and writing in inquiry are often overlooked, with primary attention placed on shaping hands-on investigations for students that will result in strong conceptual understanding. As discussed earlier, most of the NSF-funded, inquiry-based programs included little student reading material, perhaps as a reaction to the dominance of mainly-textbook-based science instruction. It is clear, however, that a new movement is underway. An increasing number of inquiry-based science programs for elementary students are introducing the use of texts in the form of science "readers" and science "notebooking"—including many NSF-supported inquiry-based curricula (e.g., Lawrence Hall of Science, n.d.; National Sciences Resource Center, n.d.). These materials are grounded in the understanding that science learning entails and benefits from embedded literacy activities and that literacy learning entails and benefits from being embedded within science inquiry. Further, some new

curricula are designed to be educative for teachers, providing resources to learn needed science content, literacy practices, and pedagogies that support student learning (Cervetti et al. in press). Cervetti, Pearson, and their colleagues at the University of California, Berkeley, have developed a curriculum—Seeds of Science/Roots of Reading—for elementary grades that intertwines science and literacy learning. Seeds/Roots is driven by learning goals in science, including understanding science concepts, the nature of science, and inquiry, and by goals in literacy, such as understanding and using science text to support inquiry at every step of the inquiry cycle.

Similarly, Greenleaf and colleagues have developed discipline-based inquiry units to support ninth grade struggling readers to develop academic literacy proficiencies that explicitly model and support the ways of reading and reasoning vital to science learning and understanding. In a ten-week unit designed to mentor and engage students in science reading and reasoning processes, students investigate the factors contributing to the epidemic increase in obesity and diabetes among American youth and ways to reverse these alarming trends. As they investigate these factors, students learn how to make sense of varied science representations– data tables, demographic statistics, nutrition labels, diagrams of the digestive and endocrine systems, graphics such as the varied food pyramids produced by the CDC over time, timelines and maps. They use a broad set of texts including textbook excerpts, science reporting in the national media, monographs from the CDC and Department of Agriculture, authoritative websites from universities, NSF, and health commissions, learning to approach these texts critically as well as scientifically. As students investigate questions about risk factors related to diabetes and obesity, they keep their own diet and exercise journals, reflecting on how these factors relate to their own health and that of their family and friends, and how science understanding and literacy can affect people's ability to take charge of their own health.

Assessment

Finally, it is important to note that all the professional development in the world will have little impact if we cannot also create more balanced assessment portfolios for our accountability systems (NAE 2009). The inclusion of challenging performance tasks—tasks that involve extended inquiry (over several days), analysis of findings, and public reports of student work—would help to promote the very sort of inquiry that research documents as effective. As long as single-answer multiple-choice tests serve as the primary metric for measuring student learning and teacher quality, not only in science but in literacy as well, it will be difficult for teachers to take the risk of promoting genuine inquiry in their classes.

Inquiry as the Common Core

As a final point, we emphasize that all of our suggestions for moving ahead are really suggestions for making inquiry the common theme of reform. Teacher learning is most profound when teachers can employ the very same inquiry processes for their own professional learning that they aspire to enact

with their students. By making their own learning about literacy and science pedagogy the object of inquiry, teachers can simultaneously develop the insights and pedagogical strategies they will need to mentor their students. Scientific literacy instruction of the sort supported by empirical research requires that the dispositions and practices of inquiry based science be appropriated for inquiry in reading and writing. And finally, we must reshape our assessment systems to better reflect the nature and goals of inquiry oriented instruction in both science and literacy. If we can manage all of these initiatives, we might be able to help teachers situate literacy and science each in the service of the other as students gain tools and proficiency in both. The agenda is surely daunting, but the costs of avoiding it are high and the rewards for pursuing it are substantial.

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