SCIENCE FOR THE NEXT GENERATION

PREPARING FOR THE NEW STANDARDS

WILLIAM BANKO, MARSHALL L. GRANT, MICHAEL E. JABOT, ALAN J. McCORMACK, AND THOMAS O'BRIEN

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CONTENTS

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CONTENTS

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CONTENTS

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FOREWORD

Early Science Education

ANSWERING THE QUESTION "WHY?"

Arne Duncan
U.S. Secretary of Education

Children, especially young children, are natural scientists. What parents haven't heard more times than they can remember their two-year-old's insistent question, "Why?" "Why is the sky blue? Why do I have to wear shoes? Why don't cats take baths?" Children's innate curiosity makes them natural scientists almost from birth.

Because children's inquisitiveness and desire to explore is so active in the early years, it is unfortunate to see that some time in elementary school, many kids lose their interest in science. Studies show that even in the early elementary grades, children are forming negative views about science, developing attitudes that can mar their educational careers. In the elementary years, children often say that science is too difficult and even dangerous. While many can easily envision themselves as future firemen, ball players, lawyers, artists, and even presidents, few young children picture themselves becoming chemists or biologists or energy entrepreneurs.

Perhaps young children do not see themselves as future scientists because in the United States students are not introduced to science early enough. Most formal science training takes place in grades 9–12, and this late start is hurting our country and our students. Recent results from the Program for International Student Assessment (PISA), a widely respected test given across the world, indicate that the United States has fallen to 21st place in science. In many of the countries that are ahead of us in science, the subject is taught in schools before the children even learn to read or write. Schools do it by introducing children at a young age to scientific inquiry: to observation, inference, and verification. They do it by integrating science thinking into early lessons in subjects like reading and social studies, even playtime. As children plant school gardens, for example, they learn to measure and observe the effects of the Sun and the rain and the bugs. In our family, we have found that the kids in elementary school are interested in these activities. My own children Claire and Ryan spent hours measuring pepper plants with their mother and me and making predictions about how big the plants would get.

Elementary science lessons can produce powerful results in children because they help them to become comfortable with science. With greater exposure to scientific concepts and to people who practice science in their careers, students can see themselves as scientists today and as the future astronauts, meteorologists, science teachers, and nurses of tomorrow. But more than that, elementary science learning enables students to think critically and begin to solve problems, laying a foundation for learning in all content areas. The kind of discovery learning that is often at the heart

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of a science lesson helps students to become truly engaged in school and excited about learning.

However, for students to benefit from classrooms built on inquiry and discovery, schools need early childhood teachers who have knowledge of early science learning and strategies that support young children's growth and development in science. Some teachers of higher grades (including middle and high school) also may benefit from professional development to hone their skills in creating science classrooms that are engaging and that model passion and excitement for science and for learning. As states reshape their curricula to ensure that students are ready for college and careers, it also makes sense for states to revisit science standards and align them to a new generation of assessments that test students' knowledge and critical-thinking skills.

More than ever, science learning is critical for our country. President Obama says, "The country that out-educates us today will out-compete us tomorrow." As a country, we need to exponentially expand the number of entrepreneurs, scientists, science teachers, and problem-solvers. We need creative thinkers who can play the lead role in reducing our nation's carbon footprint and our dependence on foreign oil through the use of second-generation biofuels, methane digesters, and energy-efficient tillage methods. We need students who can solve problems that don't yet exist and work on scientific endeavors that we haven't even thought of.

Science is essential in America's success in the knowledge economy of the 21st century. But it's not the only subject that students need to master. All of our young people need a well-rounded curriculum. In order to communicate well, to understand, and to think and inspire others, they need to be engaged readers and lively writers. They need social studies to become informed, participating citizens and mathematics to solve problems across a variety of disciplines. They need to learn social skills and be able to work with others. Students can acquire basic science literacy as they learn to read and write and study social studies and as they work together and do math. They can test theories that they read about in social studies and literature and can keep nature journals, honing writing and science literacy at the same time. What I am suggesting is not that we should supplant student experiences in other core subjects with science instruction but that we become more intentional about including science in an interdisciplinary way in all of these important subjects and about ensuring that our science instruction follows best practices for teaching early learners.

More than anything, we need science teachers to begin introducing our students to science education sooner. As parents, we know that the best way to ensure that our kids are not afraid of the water is to familiarize them with water frequently as soon as possible. So we put them in the baby pool and pour cups of water over their heads. We give them baths nightly and sign them up for swimming lessons. The result of these efforts is that instead of our kids having to get over a fear of water, they never acquire that fear. We need to apply this same approach to teaching science. Science teachers who are skilled in early learning instruction can make a tremendous impact on the life of a child by exposing her to science at an early age so that she doesn't automatically think of it as something that is too hard or boring but as a fun and interesting activity. When a kindergarten student asks, "Why are we testing to see how long it takes to turn cream into butter?" we want another child in the class to reply, "We want to learn where butter comes from, and because it's *fun!*"

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BOOK OVERVIEW

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As elementary school teachers, you have one of the most important, challenging, and rewarding missions of any professional; namely, to help parents and society launch our children into a future that both requires and provides opportunities for lifelong learning. As human cultures have evolved and become both increasingly interdependent and ever more dependent on science, technology, engineering, and mathematics (STEM), the need for and nature of formal education also has evolved. In earlier eras, indoctrinating youth in the traditional beliefs of their elders and informing youth of societal norms, expectations, and predetermined roles were sufficient. The printing press and the subsequent accelerating pace of STEM discoveries and inventions created the need for more formal instruction, especially in the 3 Rs (i.e., reading, writing, and arithmetic). For centuries, theories of learning and models of teaching typically viewed learners as relatively passive, impressionable clay that teachers shaped or as empty vessels to be filled. Thus was wisdom transferred or passed down through the ages. Today, however, a knowledge-based, global economy demands a future-focused, interactive education that reconceives the teacher as a catalyst for learner-active, minds-on construction of understanding. Rather than merely asking learners to reproduce past answers and solutions, the 21st-century educator must inspire learners to inquire and innovate.

Following the earlier release of the *Common Core State Standards* in mathematics and English language arts (which includes literacy in history, social studies, science, and technical subjects) and building on the more recent *A Framework for K–12 Science Education*, the *Next Generation Science Standards* (*NGSS*) invite teachers to be key contributors to an educational revolution. This revolution arises from ongoing and compelling research on how children and adults learn (i.e., a science of learning; see Chapters 8 and 9). The old models of teaching as simply telling and learning as passive sit-and-get listening will not meet the needs of tomorrow's citizens.

For most teacher-readers of this book, science is one of several disciplines that you are expected to teach; for some, it may be your primary area of expertise. Whatever the range of your discipline-based teaching assignment, this book is a resource to help you interpret and implement the vision of the *Framework* and the *NGSS* into your curriculum-instruction-assessment. As teachers, you are like other learners in that your prior knowledge bases and next-step learning needs probably vary. The following overview will help you determine how to approach this book. You can read straight through from the beginning to end. Or you can select the sections that are most immediately rel-

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evant to you and navigate the book in a manner analogous to progressive pathways and alternative links in internet-based searches. While some sections are more theoretical and others more pragmatic, keep in mind that "there is nothing so practical as a good theory."

The Foreword (Early Science Education: Answering the Question "Why?"), by U.S. Secretary of Education Arne Duncan, provides a national perspective on the critical role of science in the K–5 curriculum. Elementary teachers are challenged to use interdisciplinary, inquiry-oriented science lessons to build upon and extend children's innate curiosity and set the stage for their lifelong interest in and engagement with the world. The foundation for an informed, scientifically literate citizenry, as well as future scientists and engineers, is laid in the elementary grades by you, the teacher-readers of this book.

Section I, Science: A Human Adventure, is introduced by Nobel Prize–winning physicist and former U.S. Secretary of Energy Steven Chu, who reiterates the theme that preschool children are natural scientists. Dr. Chu also argues that nurturing this innate exploratory orientation in elementary school is essential for economic, energy-related, and environmental reasons. Chapter 1, What Is Science?, expands on this theme of science as an extension of our natural desire to explore our diverse world and discover unifying connections, construct explanatory theories, and invent products and processes that apply what we have learned to solve practical problems. It offers several concrete examples of how disciplinary core ideas (e.g., gravity/PS2: Motion and stability: Forces and interactions and PS3: Energy) cut across falsely conceived separate disciplines to reveal the interconnected nature of the universe. The authors suggest that elementary school science should employ an integrated, interdisciplinary approach in which skills of reading and listening, writing and speaking, and visual and mathematical ways of learning and communicating reinforce one another. A brief synopsis of the international, cross-generational contributions to our understanding of our solar system (ESS1: Earth's place in the universe) suggests that the ever-evolving story of science is also a key component of our shared history as humans. Science truly is a human adventure!

A knowledge-based, global economy demands a future-focused, interactive education.

Section II, *A Framework for K–12 Science Education*, opens with an introduction, Science and the Educated Person, by cognitive psychologist Steven Pinker, who argues that science is one of the greatest human accomplishments and an essential component of any educated person's knowledge base. The two chapters that follow help readers see how leadership from the states is ensuring that science is given an appropriate emphasis in school curriculum. Specifically, Chapter 2, High Expectations for All: From the *Common Core State Standards* to the *Next Generation Science Standards,* offers a historical overview of the shared vision, political debates, and practical challenges that gave birth to state-led, common standards in English language arts (ELA), mathematics, and science. Chapter 3, From *Framework* to *Next Generation Science*

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Standards, written by a language arts coordinator, offers a teacher-friendly synopsis of the 383-page document that provides the framework for the *NGSS*. Simple graphics and tables taken from the *NGSS* help teacher-readers see the big picture of how integrating the 8 scientific and engineering principles, 7 crosscutting concepts, and 13 disciplinary core ideas is truly "elementary."

Section III, Using the *Framework* and *NGSS* to Redesign Science Lessons, opens with an introduction, Science at the Center, by a former president of the National Academy of Sciences and current Editor-in-Chief of *Science* (an American Association for the Advancement of Science journal) Bruce Alberts. Dr. Alberts argues for re-envisioning school science as a sense-making activity, rather than an exercise in mindless memorization for fill-in-the-blank worksheets and multiple-choice exams. Elementary science should teach children how to think critically and creatively, make wise decisions, and especially to learn how to learn. Chapter 4, 5E(z) Guidelines for Designing Research-Informed Science Lesson Sequences, develops an extended analogy between the curriculum-instruction-assessment (CIA) work of teachers and the scientific and engineering practices and skills we wish to develop in our students. The BSCS 5E Instructional Model, or Teaching Cycle, of Engage, Explore, Explain, Elaborate, and Evaluate is used both as an organizing frame for the chapter and as an intelligent model for teachers to use when designing CIA units. This chapter serves as a conceptual foundation for the 5E mini-units presented in Chapters 5–7 and for 5E units to be developed later by the teacher-readers.

Section IV, The *Next Generation Science Standards* in the Classroom, opens with an introduction, Connections, by an elementary school principal who shares her enthusiasm for how integrating STEM disciplines and making connections with social studies and literacy is enriching for both students and their teachers. Chapters 5–7, Sample 5E Mini-Units for Grades K–5, presents examples of multi-day mini-units that follow the research-informed teaching cycle of Engage, Explore, Explain, Elaborate, and Evaluate. Teacher-readers can use these samples as models to help them revise their current science units to better emphasize an intentional, inquiry-oriented, constructivist sequence of lessons. Two to three samples (each) are provided for the physical, life, and Earth and space sciences. Short subsection introductions by Nobel Prize–winning brain scientist Eric Kandel and president of a state science teachers association Brian Vorwald divide the second and third subsections and present science-for-citizens arguments for making science a central curricular component of elementary education.

Section V, The New Science of Learning, opens with a brief introduction, Illuminating Minds, that focuses on a child's curiosity and drive to understand as the natural foundation for lasting lifelong learning. Chapter 8, How We Model the Complexities of the World: Learning and Memory, Systems and Function, summarizes the convergence of research from psychology, neuroscience, and other cognitive sciences that overturns earlier, but still prevalent, passive storage and retrieval models of learning and memory. An alternative view that emphasizes concepts such as adaptive malleability, cortical plasticity, and goal-driven meaning-making is presented in conjunction with related, practical pedagogical principles. The unexamined and often erroneous misconstrued metaphors that we have for learning are strong determinants of how we teach. This chapter challenges readers to embrace a research-informed perspective on the nature of learning

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and teaching that will likely resonate with and reinforce elementary teachers' learner-centered orientation to teaching.

Section VI, The New Science of Learning in the Classroom, opens with an introduction, Science Is Fun, that focuses on the natural joy that we experience when we encounter and explore diverse and sometimes initially discrepant, science phenomena. Learning and teaching science should be considered "FUNdaMENTAL" in that science unites curious questioning minds with the endless wonders of our world. Chapter 9, What Teachers Do to Engage Their Students in Learning, combines classic pedagogical wisdom and current best practices and research on learning to offer broad but pragmatic principles to aid elementary science teachers in aligning their efforts with the *Framework* and *Next Generation Science Standards*.

Section VII, Literacy and Science, opens with an introduction, The Importance of Science in Elementary School, that argues that science is a natural, social extension of the exploratory, hands-on, discovery-oriented world of preschool children and that, as such, builds on and contributes to their overall literacy and learning capabilities. Chapter 10, Science? Literacy? Synergy!, presents a research-informed argument for an inclusive definition of scientific literacy that synergistically integrates reading, writing, and reasoning from texts with inquiry-focused, experience-based science instruction. The elementary grades are an ideal setting to simultaneously develop both general and science-specific literacy skills and knowledge. Readers are directed to field-tested commercial products and given practical examples of how to accomplish the curricular literacy integration that is called for in the *Common Core State Standards* in both English language arts and mathematics.

The concluding chapter, Moving Forward: Science is Elementary!, is written by Alan McCormack, past National Science Teachers Association (NSTA) president and elementary science teaching specialist. Dr. McCormack invites teacher-readers to become active contributors to a Let's Move Forward! initiative that offers the next generation of citizens, our current elementary students, the very best research-informed, standards-based, child- and science-friendly curriculum-instruction-assessment (CIA).

Collectively, the editors and authors invite our readers to use this book (in whatever order you deem most appropriate to your needs and interests) as a resource to become teacher-leaders in the school science reform movement that is being catalyzed by the *Next Generation Science Standards*. In addition, the websites listed by the various authors, plus additional online resources, will be posted on the NSTA website (*www.nsta.org/ScienceForTheNextGen*) where they can be accessed as live links and periodically updated. Working collaboratively with fellow teachers, school administrators, teacher educators, NSTA, state teachers associations, and concerned parents, we can ensure that our children experience a science education that truly prepares them to fully appreciate our world and seek to contribute to a brighter future for their descendants.

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CHAPTER 4

5E(z) Guidelines for Designing Research-Informed Science Lesson Sequences

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Commercial textbooks, science activity books, and internet resources offer elementary teachers a plethora of science activities that claim to be "inquiry based" (NSTA 2004). Although far fewer activities meet all the S_2EE_2R criteria of being Safe, Simple, Economical (time and money), Enjoyable, Effective, and Relevant (O'Brien 2010, p. 343), a number of quality elementary science methods books are available to assist teachers in separating the wheat from the chaff (e.g., Friedl and Yourst Koontz 2004; Martin 2011; Martin et al. 2005). Overworked elementary teachers do not have to invest their limited time in creating, field-testing, and revising their own science activities from scratch. Instead, individual teachers and teacher teams can invest their precious time in exploring how to synergistically sequence a series of such activities to align with not only the *Next Generation Science Standards* (*NGSS*) but also research-informed, developmentally appropriate learning progressions. In this way, the whole science unit can become greater than the sum of its parts (i.e., the individual lessons).

Well-designed science curriculum-instruction-assessment (CIA) is like a carefully crafted book or book series in which each chapter or book in the series builds on and extends the previous one. High-quality writing (and intelligent CIA sequences) draw the reader (or student) into an ever deepening and broadening world of understanding, which both builds on and challenges their prior understandings. Great books and CIA units also create a need-to-know that propels the reader (or student) by the power of intrinsic motivation (Banilower et al. 2010; see also Chapter 8 of this book). Interestingly, this same kind of self-reinforcing feedback loop motivates scientists and engineers to keep pushing against the boundary of the known, exploring the endless frontier of new discoveries and inventions. And this is not surprising, since "science is fundamentally a social enterprise … . [T]he way that scientists operate in the real world is remarkably similar to how students operate in effective science classrooms" (Michaels, Shouse, and Schweingruber 2008, pp. 5–6).

Research-informed science lesson sequences (i.e., integrated CIA mini-units) support learning as a process of conceptual change and meaning-making where students are regularly engaged with the eight scientific and engineering practices identified in Chapter 3 of *A Framework for Science Education, K–12* (NRC 2012). Planning, implementing, and revising CIA units requires teachers to follow an analogous set of inquiry-driven practices. The following discussion integrates ideas from the *Framework* (NRC 2012) and the *BSCS 5E Instructional Model* (Bybee et al. 2006), or Teaching Cycle by drawing an extended analogy between the work of scientists and engineers and the CIA work of teachers.

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The 5E Teaching Cycle of Engage, Explore, Explain, Elaborate, and Evaluate is an instructional model for designing a series of experientially rich lessons that are conceptually linked and developmentally sequenced to support the ongoing, progressive refinement in student understanding as it develops over time (Bybee 2002). As such, it is especially effective in designing mini-units of five or more lessons in which at least one lesson is devoted to each phase of the 5E Teaching Cycle (O'Brien 2010). But depending on the learning objectives and available time, adjacent phases can be combined into shorter time frames. The underlying logic of the teaching cycle is that individual lessons only make sense in light of how they build on previous lessons and how they create the cognitive need and scaffolding for subsequent lessons. Both the individual and the collective human understanding of science are built on (and in some cases reconstruct flaws in) the foundation of prior conceptions, including resistant-to-change misconceptions (Mintzes, Wandersee, and Novak 1998; O'Brien 2011a). Similarly, intelligent CIA is designed around a cycle of learning experiences with diagnostic, formative, and summative assessments embedded in an instructional sequence that is aligned with the curriculum objectives (NSTA 2001; O'Brien 2010 and 2011b).

Let's consider, then, five steps that teachers can use to better sequence science learning experiences and how these steps are analogous to the eight scientific and engineering (S&E) practices:

1. **Engage:** Both science and science teaching begin with asking questions (science) or defining problems (engineering) [S&E Practice 1] that need to be answered or solved about some observed phenomenon or system (e.g., "I wonder what, where, when, how, or why … ?"). As such, intelligent K–5 CIA rests on the fact that like scientists and engineers, "[c]hildren are born investigators … [who] have surprisingly sophisticated ways of thinking about the real world, based in part on their direct experiences with the physical environment" (NRC 2012, p. 24).

The *Framework* (NRC 2012) frames the problem or challenge of K–12 science education as the progressive development of students' ability to "actively engage in scientific and engineering practices and apply crosscutting concepts to deepen their understanding of the core ideas" (pp. 8–9). In defining the latter, the *Framework* addresses two common deficiencies of conventional, textbook-based science curricula: (1) a mile-wide, inch-deep scope versus a more limited, developmentally appropriate set of 13 disciplinary core ideas in the physical, life, and Earth and space sciences; and (2) a failure to give sufficient attention to the recommendation that "classroom learning experiences in science need to connect with [students'] own interests and experiences" (NRC 2012, p. 28) and integrate engineering, technology, and applications of science (NRC 2012) to communicate relevance and salience.

Facilitating students' understanding of these three dimensions of science education requires teachers to recognize that every scientific concept, principle, or theory in their local district and state curriculum, was initially (and continues to serve as) an answer or solution to one or more real-world relevant questions or problems. Furthermore, "[i]n order for problems to be effective for supporting learning, they must be meaningful both from the standpoint of the discipline and from the standpoint of the learner … if students fail to see the problem as meaningful, there is little chance that they will engage in the range of

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productive science practices that result in student learning" (Michaels, Shouse, and Schweingruber 2008, pp. 127–128).

CIA units make scientific questions or problems meaningful to students by beginning with activities that engage them with one or more "FUNomena" to activate their natural curiosity, focus their attention, and generate a need-to-know motivation (O'Brien 2010). In contrast, conventional instruction begins with teacher and textbook-based, premature answers and solutions, rather than with rich, pregnant problems that have the potential to develop improved student understandings. Stating curricular objectives in the form of questions-to-be-answered leads teachers to consider a range of differentiated instructional strategies to engage students with the question(s) (Gregory and Hammerman 2008; O'Brien 2011b, Appendix A). Minds-on, discrepant event-type demonstrations; hands-on explorations with surprising outcomes (O'Brien 2010, 2011a, and 2011b); and multimedia-based invitations to inquiry and puzzle-like reading passages (e.g., Scholastic's *Magic School Bus* books and DVDs and Dan Sobel's *Encyclopedia Brown* short stories) all serve the purpose of raising questions. The questions that students generate from experiencing such FUNomena (with teacher prompting and assistance as needed) challenge them to activate relevant prior knowledge and to consider whether they might need a "cognitive upgrade." Student- and teacher-generated questions also provide a diagnostic assessment of students' prior knowledge that is analogous to a second, important aspect of science and engineering.

2. **Explore:** In framing researchable questions and planning and carrying out Exploratory investigations [S&E Practice 3], scientists and engineers attempt to make explicit their prior conceptions and assumptions about the system being studied. Given the adaptive malleable nature and cortical plasticity of the human brain (see Chapter 8) and the integrated, systems-based complexity of nature, the fields of science and engineering develop and use models [S&E Practice 2] that are forever subject to reconstruction, renovation, and expansion. Both our individual and discipline-wide prior conceptions contain a mix of valid conceptual models that need to be recovered and built on; misconceptions that need to be uncovered and displaced (e.g., Driver et al. 1994; Duit 2009); and conceptual holes that need to be discovered and filled. While no individual or series of investigations can ever absolutely prove the validity of a given hypothesis, they can provide data that either support or contradict it. Investigations attempt to test and extend the limits of prior understanding (i.e., theory-driven challenges to our comfort zones) and are often motivated by puzzles, discrepant data, or anomalies (i.e., things that don't seem to work as we think they should). Thus problem finding is a desired goal and "miss-takes" are viewed as catalysts for further research. Scientists and engineers have a habit of mind that causes them to look critically and creatively at both unanswered questions and unquestioned answers about how things work. Their research is systematic, with intentionally designed and articulated plans for data collection and analysis in light of a given hypothesis. But their plans are also flexible and adaptive to new, unanticipated barriers or serendipitous occurrences (e.g., Pasteur's "chance favors the prepared mind").

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Similarly, teachers bring a set of tacit beliefs and assumptions about the nature of science, teaching, and learning to their curricular planning. Documents such as the *Framework*, the *NGSS*, and this book are designed to challenge teachers to consider the unquestioned answers of their prior beliefs and practices. For instance, a "common but limited approach to sequencing investigations has been to teach the content related to the investigation first, and afterward do the investigation in order to validate the content" (Michaels, Shouse, and Schweingruber 2008, p. 129). Laboratory exercises that follow, rather than explorations that precede, teacher and textbook-based explanations have been cited as a primary reason for the failure of laboratory-based learning to achieve its full potential (NSTA 2007; Singer, Hilton, and Schweingruber 2006). Accordingly, the 5E Model intentionally places the Explore phase immediately after the Engage phase to continue the Engage phase's emphasis on "FUNomena first, facts follow/Wow and wonder before words" (O'Brien 2010, 2011a and b). However, it is important to note that typically "students are not sent off on an unguided exploration of a phenomenon or question, but are presented with intentionally sequenced and supported experiences framed in a sustained investigation of a central problem" (Michaels, Shouse, and Schweingruber 2008, p. 129). Simply having students participate hands-on does not guarantee minds-on cognitive processing.

Guided, inquiry-based investigations that ask students to predict, observe, explain (POE) help ensure that student hands-on explorations are "FUNdaMENTAL" in two senses of the word (O'Brien 2011b, p. xviii). First, they involve both emotionally engaging play and minds-on, mentally engaging cognitive processing. Second, they develop students' facility with using fundamental science and engineering practices, crosscutting concepts, and core ideas (i.e., the three dimensions of the *Framework*). During the Explore phase, the teacher plays the role of the "guide on the side" (rather than "sage on the stage"), helping small cooperative learning groups of two to four students carry out hands-on activities (and/or computer-based simulations) and record and organize their observations. Teachers also model and assess student lab skills (for safety skills, see Kwan and Texley 2002; NSTA 2007) and actively scaffold and monitor student learning with probing questions without providing premature answers. Explore phase investigations are analogous to a farmer who hoes a field to dislodge weeds and rocks (i.e., activates and challenges misconceptions) and provides fertilizer that prepares the soil (i.e., experiential grounding of conceptual precursors) to support new seeds (i.e., scientific concepts). Student explorations also lead the way to a third phase of the 5E Model and additional scientific and engineering practices.

3. **Explain:** Scientists and engineers regularly analyze and interpret data [S&E Practice 4] obtained from their investigations, often using mathematics and computational thinking [S&E Practice 5], and engage in argument from evidence [S&E Practice 7] to construct explanations (science) and design solutions (engineering) [S&E Practice 6].

Similarly, students who have gained empirical evidence in the Engage and Explore phases are challenged in the Explain phase to develop, discuss, and debate evidence-based explanations for the FUNomena they've experienced. During the Explain phase, teachers challenge the students to make sense of data gathered from the Engage and Explore phases. At least part of the story hidden in the data can be revealed by inviting students

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to make evidence-based arguments in which they propose and critique both complementary and competing claims with an eye to collaboratively constructing the best ideas (rather than winning an argument in the traditional combative sense of the term). Teachers can use modeling and explicit instruction to teach students strategies such as restating what a peer has said to check for understanding; asking clarifying, analytical questions that probe the connections between claims and the evidence gathered (and allowing sufficient wait time for thoughtful answers); and piggybacking off the ideas (and data) of peers to generate creative synthesis. Teaching students how to have productive, collegial conversations models what scientists and engineers do in the course of their work and what concerned citizens should do as participants in a democracy (see Bergman's discussion of Socratic seminars in Chapter 9).

During the Explain phase, teachers may introduce age-appropriate mathematics; individual and group readings and related writing activities from textbooks, tradebooks, science magazines, and so on; physical models and analogies that help make abstract ideas more concrete (Gilbert and Ireton 2003; Harrison and Coll 2008); and multimedia presentations and simulations that help bridge the gap between students' original ideas and scientifically valid conceptions. The key is that the teacher helps students construct sensible (i.e., sense-based and logical) explanations versus over-relying on either the teacher or textbook as the absolute source of the authoritative answer irrespective of the data collected. If the latter is necessary to save an activity, it is likely that the teacher used a poor-quality activity or introduced a concept beyond the specific grade band of the students (K–2, 3–5 or 6–8). Of course, after productive student discussions based on their data has gone as far as possible, teachers will need to formally introduce scientific concepts, principles, and terminology. But even during the Explain phase, teachers' words and actions are less about indoctrinating or informing students about the right answer and more about instructing and inspiring them to individually and collectively reconstruct their prior ideas in light of new, compelling, empirical evidence. Learning science is a process of continual conceptual change based on evidence (NRC 2007).

Equity and excellence are achieved as an outcome of teaching students the importance of respecting different views; playing devil's advocates with their own ideas; and working collaboratively toward the best answers based on empirical evidence, logical argument, and skeptical review (NRC 1996). This ever-evolving narrative of discovery is very different from the rhetoric of conclusions approach to learning science. Inquiry-based, constructivist-oriented science instruction has the added benefit of accurately portraying how we know what we know in science. Thus students learn through direct experience about the nature of science as a way of knowing that is similar to yet distinct from other disciplines (NSTA 2000). More broadly, "exemplary science education can offer a rich context for developing many 21st-century skills, such as critical thinking, problem solving, and information literacy, especially when instruction addresses the nature of science and promotes use of science practices. These skills not only contribute to the development of a well-prepared workforce of the future but also give individuals life skills that help them succeed" (NSTA 2011, p. 1).

Students' ability to obtain, evaluate and communicate information [S&E Practice 8] and engage in collaborative discussions about claims, evidence, and reasoning provides formative

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assessment data. This data informs the teacher's subsequent actions that may require modification of her/his prior assumptions about students' abilities and how to best serve their learning needs. Learning-to-read/reading-to-learn; learning-to-write/writing-to-learn; and drawing and graphical organizer-based activities (e.g., concept mapping and graphs) are especially powerful when students have a need to construct explanations for FUNomena they've experienced in the two previous phases. True scientific literacy requires explicit attention to students' general English language arts (ELA) literacy skills, science-specific literacy demands, and the synergy between the two. (For more background on the science-literacy connection, see AAAS 2010; Douglas and Worth 2006; Saul 2004; Thier 2002; Wellington and Osborne 2001; and Chapter 10). Although the *Framework* tells us that "every science or engineering lesson is in part a language lesson" (NRC 2012, p. 76), learning to use the written and spoken language of science (including mathematics) is necessary but not sufficient for learning science. The real power in science (and the real test of learning) comes when students can use their revised conceptions to accurately predict, observe, and explain new FUNomena related to those they've experienced in the first three phases of the 5E Model. This application and extension occurs in the fourth phase of the 5E Model.

4. **Elaborate:** The generalizability and power of scientists' and engineers' refined explanations and solutions are put to the test when they are applied to related but seemingly new or different contexts. In contrast to popular misunderstanding about the nature of science, scientific theories are inherently parsimonious (NRC 2012, p. 48). That is, a limited set of broadly applicable crosscutting concepts (7) and disciplinary core ideas (13) are tightly interconnected to provide powerful explanatory and exploratory tools. Combined, these big ideas both account for the known and provide a compass or GPS to lead us into previously uncharted waters by triangulating from known points of reference.

Similarly, in the Elaboration phase, teachers introduce new activities in which students are challenged to apply and extend what they've learned in seemingly different but related contexts. Real-world applications and new challenges, problems, or tasks solidify and broaden students' understanding about the implications of what they've learned. These applications also provide another opportunity for students to experience the "Eureka, I got it!" effect. During this phase, all the lessons learned from the previous activities should be brought together and synergistically integrated into a sensible whole that is greater than the sum of the parts. The formative assessment aspect of the Elaboration phase provides additional cognitive scaffolding and lets both the students and teachers know whether the students are ready for the final summative evaluation phase.

5. **Evaluate:** The final test of the work of scientists and engineers occurs when they submit their results for publication in journals or their product designs for patent review, a process in which peers judge the quality and originality of the scientists' or engineers' work. Because of this public reporting requirement, future research and practice build on and improve the past. Subsequent research may fill in missing pieces of the puzzle, extend previous ideas into new applications (i.e., expand the field of view of the puzzle), or occasionally require reconceptualization of

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what was thought to be true, which in light of additional testing, isn't so. In any case, science and engineering are progressive human endeavors because their practitioners build on prior work (i.e., Isaac Newton's "standing on the shoulders of giants") *and* are subject to subsequent revision (see, for example, Chapter 1).

Summative assessment of student work in the fifth and final Evaluation phase can take a variety of forms beyond conventional pencil-and-paper tests. Individuals and teams of students can demonstrate their learning via a wide variety of means such as constructing models, displays, graphic organizers, or artwork with linked oral presentations for their classmates; completing a related at-home experiment; and composing written reports to their teacher, letters to their parents or younger siblings or classes, or science songs or poems for posting on a real or virtual bulletin board (Harris Freedman 1999). Regardless of the means, formal summative evaluation should inspire student interest in further scientific investigations and inform their teachers of their readiness to move forward to new topics. Thus, the end of one 5E Teaching Cycle is really the launching pad to the next one, just as the published work of scientists and engineers serves as a catalyst for further research.

The *Framework* and *NGSS* call for the development of learning progressions (NRC 2007) that scaffold student understanding of scientific and engineering practices, crosscutting concepts, and disciplinary core ideas across the K–12 grades. The *Common Core State Standards* (*CCSS*), *English Language Arts* and *CCSS, Mathematics* (NGAC and CCSSO 2010; see also Chapter 2 of this book) further challenge teachers, curriculum developers, and textbook publishers to consider how to articulate and integrate these core disciplines with elementary science (NSTA 2002). This kind of horizontally integrated (i.e., across subjects at the same grade level) and vertically articulated (i.e., within subjects across grade levels), spiral curricular scope and sequence goes beyond the time, abilities, and resources of individual teachers (and most school districts) to develop. However, as researchers continue to identify more precisely the learning progressions that relate to the three dimensions of the *Framework*, teachers and school districts will be challenged to field-test and improve these ongoing works-in-progress.

Effective science teaching requires teachers and schools to practice what they preach with respect to engaging in scientific and engineering practices to inform their teaching and take their practice to progressively higher levels. Effective teachers use lessons learned from the design, implementation, and evaluation of integrated curriculum-instruction-assessment (CIA) units to not only enrich their students' understanding but also to expand their own science content and pedagogical content knowledge (Cochran 1997). Furthermore, analogous to scientists, teachers exchange the wisdom of practice across professional collaborative networks that extend beyond the confines of their individual classrooms (or learning laboratories) and schools (NSTA 2010).

Learning to integrate the science and engineering practices and the 5E Teaching Cycle unit design is as easy as ABC. As a start, this book invites its teacher-readers to

1. **A**ctively align their individual science curriculum-instruction-assessment practices in light of the research-informed, "less is more" orientation of the *Next Generation Science Standards* (*NGSS*) (i.e., explore a reduced number of more central, age-appropriate

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concepts in greater depth). Instead of waiting for your district to purchase the "next generation" of science textbooks, you can use the sample 5E teaching cycle units in Chapters 5–7 as models for how to sequence consecutive science lessons (obtained from a variety of book and internet sources) into constructivist mini-units;

2. **B**uild better-coordinated science programs with their districts' fellow K–5 teachers (and, at the upper elementary level, their grades 6–8 colleagues) to achieve the developmentally appropriate learning progressions called for by the *NGSS*. Talented teachers can accomplish this despite outdated science textbooks, tests, and technologies, but it will require redistributing some topics across the grades and paring down the number of topics taught; and

3. **C**reatively collaborate with science teaching colleagues within and beyond their school, district, and state. Most state-level science teaching professional associations coordinate with geographically distributed sections within their state and with the National Science Teachers Association (NSTA). Being a member of a professional network provides ongoing opportunities to exchange wonderful ideas and best practices for teaching children science and to become a part of an epidemic of excellence in elementary science education! Together, an interdependent *we* can synergistically achieve more than an isolated, independent *me*. Remember, networks make it "E (z)" to produce a higher quantity and quality of "net work" that reflects the FUNdaMENTAL nature of science.

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Resources From the National Science Teachers Association

NSTA Position Statements

2000. Nature of science: *www.nsta.org/about/positions/natureofscience.aspx*

2001. Assessment: *www.nsta.org/about/positions/assessment.aspx*

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2002. Elementary school science: *www.nsta.org/about/positions/elementary.aspx*
2004*:* Scientific inquiry: *www.nsta.org/about/positions/inquiry.aspx*
2007. The integral role of laboratory investigations in science instruction: *www.nsta.org/about/positions/laboratory.aspx*
2007. Liability of science educators for laboratory safety: *www.nsta.org/about/positions/liability.aspx*
2010. Principles of professionalism for science educators: *www.nsta.org/about/positions/professionalism.aspx*
2011. Quality science education and 21st century skills: *www.nsta.org/about/positions/21stcentury.aspx*

Brain-Powered Science
www.nsta.org/publications/press/brainpowered.aspx. See also the extensive list of internet-based resources at *www.nsta.org/publications/press/extras.*

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INDEX

*Page numbers printed in **boldface** type refer to tables or figures.*

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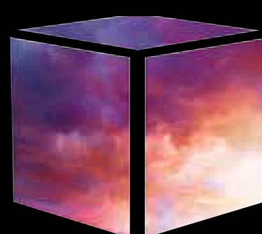

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