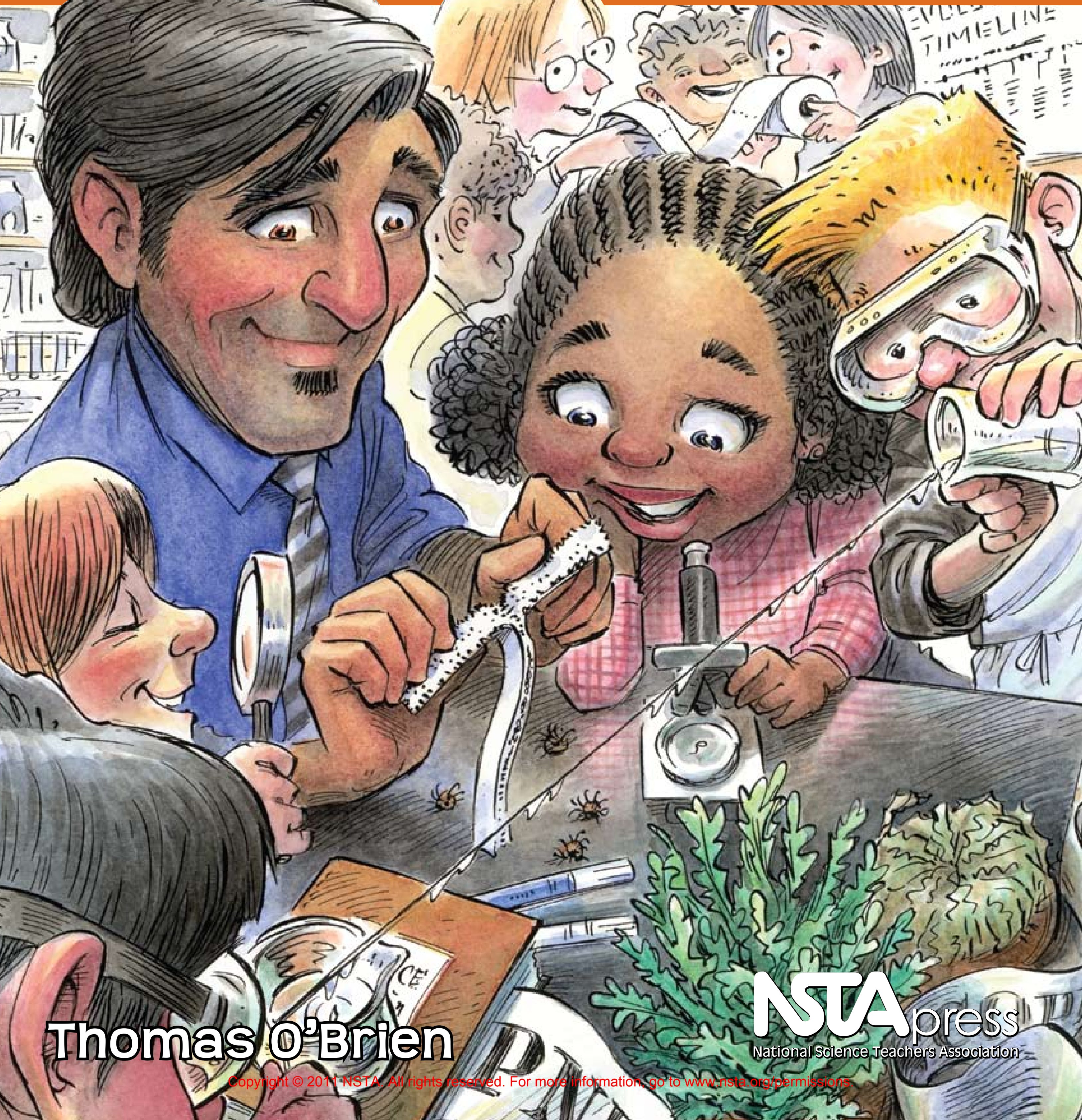
Even More Brain-Powered Science

Teaching and Learning With Discrepant Events



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NSTA press
National Science Teachers Association

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Arlington, VA

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About the Cover—Safety Issues: In the cartoon drawing on the cover, artist Dan Vasconcellos depicts the energy and excitement present in a school science lab. During actual school lab investigations, students should always maintain a safe distance from the teacher who is doing the demonstration. The teacher and students should wear personal protection equipment if the demonstration has any potential for bodily harm. Safety Notes throughout this book spell out when a demonstration requires that the teacher and students wear safety goggles or other protective items.

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Acknowledgments

As I complete this third book in my *Brain-Powered Science* series, I once again owe a debt of gratitude to my former science teachers, past and present colleagues, students, and authors who have informed and inspired my passion for teaching and learning with discrepant events.

I would also like to especially thank members of the NSTA Press staff with whom I've had the pleasure to work with and learn from since my initial meeting with Claire Reinburg, director of NSTA Press, at the NSTA National Conference in Boston in March 2008. Claire's interest in my dual-purpose use of discrepant-event activities as model science-inquiry lessons and visual participatory analogies for science teacher education encouraged me to continue refining my preliminary draft. Rather than restrict the scope of my vision, she wisely counseled me to think in terms of a book series rather than a single book. Without her encouragement and support, this series would not be in print. NSTA editors Judy Cusick (*Brain-Powered Science*) and Wendy Rubin (*More Brain-Powered Science* and *Even More Brain-Powered Science*) and illustrator Daniel Vasconcellos deserve credit for their contributions to the book's written and visual appeal. Finally, I appreciate the ongoing efforts of the NSTA marketing department to promote this book to middle and high school science teachers and college science teacher educators.

Finally, I would like to acknowledge the unnamed reviewers and teacher-readers of this book for your dedication to your students' learning and to your own professional development and that of your peers. Your transformational leadership inside and outside your classroom, department, and school can play a catalytic role in making world-class science curriculum-instruction-assessment the norm in U.S. schools. Thank you for investing your money and time in buying, reading, using, and sharing this book. With your further refinement, I believe these activities will generate rich dividends for you, your students, and your colleagues.

About the Author

Dr. Thomas O'Brien's 33 years in science education began in K–12 schools, where he taught general, environmental, and physical sciences and high school chemistry. For the past 23 years, he has directed the preservice and inservice graduate-level science teacher–education programs of the School of Education at Binghamton University (State University of New York [SUNY]). His master's-level courses include Philosophical and Theoretical Foundations of Science Teaching, Curriculum and Teaching in Science, and Elementary Science Content and Methods. He also supervises the student teaching practica. In addition, he teaches a cross-listed doctoral/post-master's educational leadership course.

Concurrent with and subsequent to earning a master's degree and doctorate in Curriculum and Instruction/Science Education at the University of Maryland–College Park, Dr. O'Brien served as a curriculum development specialist and Teacher's Guide editor on the first edition of the American Chemical Society's *Chemistry in the Community* (1988) textbook and as the coauthor of the *New York Science, Technology & Society Education Project Teacher Guide* (1996).

As a science teacher professional development specialist, he has co-taught more than 25 summer institutes, including national programs of the Institute for Chemical Education and state and regional programs funded by grants from the National Science Foundation, the Howard Hughes Medical Institute, and the New York State Education Department, among others. He has received awards for excellence in teaching and/or service from the American Chemical Society (for National Chemistry Week programs), the New York State Association of Teacher Educators, the SUNY chancellor, and the New York State Science Education Leadership Association. These grants and awards are a reflection of collaborations with university-based colleagues and what he has learned with and from the large number of K–12 teachers he has had the privilege to serve. The *Brain-Powered Science* book series owes a debt of gratitude to these friends and funding agencies for the insights and opportunities they offered the author.

Introduction

This is the third book in a series designed for grades 5–12 preservice and inservice science teachers and teacher educators. Like its predecessors, this volume features *discrepant-event* activities that can be used for two related but distinct purposes. First, these initially anomalous demonstration-experiments are designed as models of interactive, inquiry-oriented activities (NRC 2000; NSTA 2004a) for teachers to experience as "learners" *and* use as teachers in their own classrooms. Engaging learners' attention and natural curiosity and catalyzing a need-to-know motivation are the first steps to unleashing the power of the human mind. As such, these activities elicit unanswered questions and challenge unquestioned answers about the content and nature of science. Second, these same discrepant-event activities are also presented as *visual participatory analogies for science teacher education*. Used as analogies, they create an experiential context and conceptual bridge for teachers to critically examine principles of research-informed, standards-based, best-practice curriculum-instruction-assessment (CIA).

The synergy created by combining these two effective instructional strategies opens the doors to both enhanced teacher and student learning (see Appendix A for other minds-on strategies for teaching [MOST]). More than being simply a compilation of engaging science "tricks," this book series supports thought-provoking, work-embedded professional development that emphasizes action in and critical reflection on practices that make a difference in the teacher-readers' classrooms. To help ensure this applicability, the activities are designed to be safe, simple, economical, enjoyable, effective, and relevant for use in both teacher professional development *and* grades 5–12 classroom contexts (O'Brien 2010, Appendix A).

As science teachers, we work in an era of American and world history that could certainly be considered both the best of times and the worst of times. Interrelated economic, energy, environmental, educational, and ethical challenges are cited in both the daily news and scholarly reports. These challenges can be viewed either as crises that require an attribution of blame or as opportunities to apply research-informed, system-level strategies for changing the way we do things. Or, as Albert Einstein supposedly said, "The significant problems we face cannot be solved at the same level of thinking we were at when we created them" (Calaprice 2011, p. 476). In the education domain, numerous reports document that more intelligent science CIA systems are needed to meet the challenges of the 21st century (Appendix B; Hilton 2010; NAS 2007; NCEE 1983; NCMST 2000; NSB 2006; Partnership for 21st Century Skills 2009; Rotherham and Willingham 2010; STEM Education Coalition).

Research-informed pedagogical models that synergistically integrate versus simplistically sequence CIA (e.g., the 5E Teaching Cycle) and innovative education technologies are making "science for all Americans" an achievable goal rather than simply an idealistic slogan. "Mile-wide, inch-deep" curricula that "leave students with fragmented elements of knowledge and little sense of the intellectual and creative achievements of science or its explanatory coherence … [and] understanding of the practices of science and engineering" (NRC 2010a) are recognized as being in need of replacement. Preliminary work on grade-level and cross-grade-level *learning progressions* and a renewed focus on what are now being called *cross-cutting science concepts* promise to inform and reform science textbooks and state-mandated tests (Appendix C; NRC 2007, 2010a). Improvements in textbooks, technologies, and tests notwithstanding, research identifies a fourth *T*, the teacher, as the most critical external element for improving student achievement (NCMST 2000; NCTAF 1996, 1997; NRC 2010b; NSB 2006; NSTA 2007a; PCAST 2010). Caring, competent, and committed teachers inform, instruct, and inspire student-learners. The motivational and cognitive scaffolding teachers offer to students helps them co-construct the foundation for a more promising future. The cement that holds this foundation together is teachers' professional development, which extends from preservice education to a mentored induction period for novice teachers and career-long inservice education.

Unfortunately, "[t]here is a mismatch between the kind of teaching and learning teachers are now expected to pursue with their students and the teaching they experience in their own professional education" (NCTAF 1996, p. 84). "Professional development that supports student learning is rooted in the science that teachers teach and includes opportunities to learn about science, about current research on how children learn science and about how to teach science" (NRC 2007, p. 296). This book series' dual-purpose science and science-education activities provide a resource for creating these kinds of learning opportunities for teachers. Whether you are a preservice or an inservice teacher seeking a stimulus for self-reflection or a catalyst for collegial collaboration, the *Brain-Powered Science* series is for you. The embedded, holographic nature of the science education concepts allows the individual activities to be used in any sequence within and across the series. The books also provide an experiential base and models from which teachers can learn how to adapt and improve (versus merely adopt and use) science-inquiry activities found on the internet and in other science demonstration books (e.g., Becker 1993; Bell 2008; Bilash 1997; Bilash and Shields 2001; Bilash, Gross, and Koob 2006; Camp and Clement 1994; Cunningham and Herr 2002; Ehrlich 1990, 1997; Freier and Anderson 1981; Gross, Holzer, and Colangelo 2001; Ingram 2003; Jewett 1994, 1996; Kardos 2003; Keeley, Eberle, and Farrin 2005; Keeley, Eberle, and Tugel 2007; Sae 1996; Sarquis, Williams, and Sarquis 1995; Sarquis et al. 2009, 2010; Stepans 1994; Summerlin and Ealy 1988; Taylor, Poth, and Portman 1995; VanCleave 1989, 1990, 1991). Teacher-readers are also encouraged to expand their use of science analogies (Gilbert and Watt Ireton 2003; Hackney and Wandersee 2002; Harrison and Coll 2008; Lawson 1993).

Contexts in Which to Use This Book Series (For New Readers)

Preservice Science Teaching Methods Courses

The science-education focus of this three-book series correlates with topics that are typically covered in middle and secondary science-education methods courses. Any combination of the books can be used as either activity-oriented *supplements* to popular science teaching methods books or, if combined with instructor-selected readings, as a *substitute* for such books (e.g., Bybee, Carlson Powell, and Trowbridge 2008; Chiappetta and Koballa 2010; Gallagher 2007; Lawson 2010). College science teacher educators can use the dual-purpose activities with their preservice students as "walk the talk" models of inquiry-oriented, discrepant event–centered science teaching and/or as *visual participatory analogies* that provide a common experiential base to catalyze conversations about cognitive learning theory and research-informed best practices. The preservice students can use the activities in their roles as teachers-in-training during in-class microteach presentations and during their student teaching. In the latter context, section III's focus on 5E mini units is especially helpful in that it challenges the misconception that great teaching is about individual lessons rather than well-designed, multiday instructional sequences (and ultimately a course's overall scope and sequence). Similarly, section II's focus on reading in science challenges the misconception that equates "hands-off" with "minds-off."

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Grades 5–12 Science Classrooms: A Place for Teacher Learning

Effective science teaching depends on a teacher's ability to construct multi-lane, bidirectional bridges that connect the subject matter and students. Teachers must develop, creatively apply, and continually nurture their own science pedagogical content knowledge (PCK). PCK includes

> the most useful forms of representation of those [discipline specific] ideas, the most powerful analogies, illustrations, examples, explanations, and demonstrations—in a word, the ways of representing and formulating the subject that make it comprehensible to others … [It] also includes an understanding of what makes the learning of specific concepts easy or difficult: the conceptions and preconceptions that students of different ages and backgrounds bring with them to the learning. (Shulman 1986, p. 9; see also Cochran 1997; Hagevvik et al. 2010; NSTA 2003, 2004b; Shulman 1987)

Unfortunately, especially during the first few years of their careers, when they need the most support, many novice inservice teachers have limited time and external support for discipline-specific professional development. Additionally, more than one third of new teachers leave the profession within their first five years (Ingersoll 2003). Though this high attrition rate supports calls for high-quality, formalized mentoring and induction programs (Rhoton and Bowers 2003), individual teachers also can learn from their own daily planning and practice on the job.

This book is not written for casual, "on your seat" reading. Instead, the activities should be implemented on your feet in grades 5–12 classrooms and refined based on the teacher-readers' reflections on their own performance, their students' reactions, and the validity of the underlying pedagogical theories and strategies. The Science Education Concepts and Debriefing components of each activity encourage critical reflective practice (Schön 1983) that has direct transfer implications for teachers' CIA practices. The Internet Connections and Extensions provide support for each teacher's own self-directed professional development (as well as for collegial collaborations).

Professional Development Learning Communities for Inservice Teachers

An assumption of schools is that an individual student's cognitive growth (i.e., learning) is best supported in socially interactive, experientially rich, collaborative environments (i.e., classrooms) with scaffolded support provided by a master teacher (i.e., leader). Similarly, if schools aspire to be learning organizations for their students, they also need to be learning organizations for their teaching staff by deliberate design rather than happenstance. Research on building professional learning communities (PLCs) within and across schools and districts has been occurring for more than a decade (Banilower et al. 2006; DuFour and Eaker 1998; Garet et al. 2001; Hord and Summers 2008; Loucks-Horsley et al. 1998; Mundry and Stiles 2009; NRC 2001a; NSDC 2001; NSTA 2006, 2007a, 2007b; Tobias and Baffert 2010; Yager 2005). Different PLC models vary in the degree to which they provide centralized leadership from internal curriculum or professional development specialists and external consultants. However, most PLCs include a focus on curriculum-instruction-assessment and some form of lesson study as a kind of collegial research and development where teachers give and receive critical friends-type feedback on their actual practice (Coalition of Essential Schools Northwest; Dubin 2009; Lewis and Tsuchida 1998; Stigler and Hiebert 1999). Teacher-reflective practice and professional collaboration are also featured in national standards for teaching (e.g., Standards #9 and #10 in CCSSO 2010; Standards X and XI in NBPTS 2003a; Standards XII and XIII in NBPTS 2003b).

This book series supports both small and informal or larger, more formal teachers-helping-teachers networks that encourage dynamic two-way interactions between theory and practice within and between middle and secondary schools as applied research and development learning laboratories, and colleges and universities that offer preservice and inservice teacher education. The dual-purpose activities feature both science content and pedagogical content knowledge and their relationship to the *nature of science* (NOS) (Abd-El-Khalik, Bell, and Lederman 1998; Aicken 1991; Allchin 2004; Bell 2008; Clough 2004; Cromer 1993; Lederman 1992, 1999; Lederman and Neiss 1997; McComas 1996, 1998, 2004; NSTA 2000; Wolpert 1992) and the *nature of teaching and learning* (APA 1997; Armstrong 2000; Banilower et al. 2008; Bransford, Brown, and Cocking et al. 1999a, 1999b; Brooks and Brooks 1999; Bybee 2002; Cocking, Mestre, and Brown 2000; Donovan and Bransford 2005; Gardner 1999; Goleman 1995; McCombs and Whisler 1997; Michael and Modell 2003; Michaels, Shouse, and Schweingruber 2008; Mintzes, Wandersee, and Novak 1998, 2000; Tobias and Duffy 2009).

Organizational Structure of the Book

This book's approximately 80 interactive experiential learning activities are clustered into three sections (i.e., a total of five activities in sections 1 and 2; section 3 has eight 5E mini units that each contain three or more distinct activities, and about 42 Extension activities). Additionally, four appendixes provide background information on the underlying pedagogy.

Section 1. Welcome Back to Interactive Teaching and Experiential Participatory Learning

As in the first two books in this series, the first section of this book is designed to introduce the book's principle pedagogical questions, instructional approaches, and underlying assumptions about teaching and learning. The assumptions about teaching and learning include the following ideas:

1. Intelligence is not primarily genetically determined and limited, and therefore the learning environments within classrooms and the cultures of schools matter (Nisbett 2009).
2. Optimizing learning in schools depends on intelligent, research-informed curriculum-instruction-assessment (CIA) systems that are intentionally designed and cognitively and emotionally motivational, and that feature sense-making interactions between students, teachers, engaging phenomena, and the big ideas of the discipline.
3. Discrepant-event science activities and analogies are powerful instructional tools that align with these assumptions (O'Brien 1991, 1993, 2010).
4. Teachers' professional development related to both science content and pedagogical content knowledge should reflect and model what we know about learning (NCTAF 1996, 1997; NRC 1996, 2010b; O'Brien 2010; PCAST 2010).

The first activity ("Science and Art") is discrepant in that it challenges learners (with words and optional but highly recommended visuals and simple discrepant-event demonstrations) to question how science is similar to—rather than completely different from—art. Accordingly, the activity reintroduces the idea of "science as a way of knowing" that was explicitly featured in section 2 of *More Brain-Powered Science*. The first Extension activity challenges teachers and their students to brainstorm a rationale for the national goal of science for all Americans (Rutherford and Ahlgren 1991) and consider the corresponding implications for the kind of science CIA most appropriate to achieve the desired objectives. As such, the Extension serves as an anticipatory set for the book's longest section (section 3), which focuses on 5E Teaching Cycle–based mini units. Also, as one of only two mixer activities in this book, the activity is designed to help develop a collaborative culture between science teaching and learning as a "team sport." The second activity ("Acronyms and Acrostics Articulate Attributes of Science [and Science Teaching]") can be used with an optional chemistry-related discrepant-event demonstration to make students and teachers more aware of their prior conceptions and implicit beliefs about the nature of science and teaching. "Acronyms and Acrostics" also introduces a minds-on mnemonic strategy as a way to help students learn how to remember scientific terms. As such, Activity #2 can be used as a playful introduction to section 2's focus on reading as an inquiry-oriented process. Additionally, the first Extension activity invites teachers to question the answers of their prior teaching and learning experiences as a framework for yearlong face-to-face or electronically facilitated professional development.

Section 2. Reading, Student Construction of Meaning, and Inquiry-Oriented Science Instruction

For many teachers, the inclusion of a section (activities #3–#5) on reading in a book series that features phenomena-centered, minds-on inquiry-based activities may seem discrepant in and of itself. The following passage from *A Framework for Science Education: Preliminary Public Draft* (NRC 2010a) provides a compelling rationale for this section:

> Researchers have demonstrated the centrality of reading to the practice of science, showing that on average, scientists read for 553 hours per year or 23% of total work time. When the activities of speaking and writing are included as well, the scientists in their study spent on average 58% of their total working time in communication or working in the coordination space … Thus the dominant practice in science and engineering is not "hands-on" manipulation of the material world but rather a "minds-on" social and cognitive engagement with ideas, evidence and argument. Reading, for instance, is an act of inquiry into meaning—an attempt to construct sense from the multiple forms of representation used in science—words, symbols, mathematics, charts, graphs and visualizations [ch. 5, p. 6] …

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> Being literate in science and engineering requires the ability to construct meaning from informational texts … Reading and interpreting those texts is a fundamental practice of science. Any education in science or engineering needs, therefore, to develop students' ability to read and to produce written text [ch. 5, p. 20] … As such every science or engineering lesson is a language lesson. [ch. 5, p. 21]

The validity of this passage notwithstanding, several common, pedagogically problematic misconceptions suggest this section on reading and science is warranted:

1. By fifth grade, most students have (or should have) successfully transitioned from learning to read to reading to learn.
2. Reading science textbooks is similar to reading other textbooks, fictional stories, or popular print-based media and does not require any special word-decoding skills and information-processing or metacognitive strategies.
3. Teaching students how to read is the sole responsibility and expertise of English language arts and reading teachers.
4. Reading about science is the antithesis of doing "real" inquiry-based science.
5. Reading to learn and learning how to read science textbooks are not essential, FUNdaMENTAL* components of grades 5–12 science classrooms.

Section 2 is designed to challenge these misconceptions with fun minds-on, inquiry-oriented activities that teachers can experience as learners and use with their own grades 5–12 students. Learning how to negotiate one's way through the "language labyrinth" can and should be a playful part of learning science.

Section 2 helps set the stage for section 3 in that brief inquiry-oriented reading passages (e.g., history-of-science case studies and present-day science-in-the-news articles) drawn from internet sites, popular science-type journals, and other science news sources can be used as a complement to phenomena-based discrepant-event Engage- and Explore-phase activities. These kinds of passages raise interesting questions (rather than offer answers) and help establish a motivational need-to-know context and problem-solving situation that demands further investigation. More conventional science textbook passages can be productively used both as in-class, guided reading activities and out-of-

* The interactions between teachers, learners, and FUNomena should be FUNdaMENTAL in two senses of the word. First, they should be both emotionally engaging (fun) and cognitively stimulating (mental). Second, they should develop core scientific concepts ("big ideas") that serve as the theoretical and conceptual foundations (or "forest") for contextualizing additional related concepts (or "trees")

class homework assignments during the Explain and Elaboration phases. And of course, reading is a necessary prerequisite for most kinds of performance during the Evaluation phase. As learners become more skilled as readers, their motivation and ability to pursue independent reading outside of school helps them become more scientifically literate lifelong learners. Science-content-based literacy skills are essential components of an intelligent curriculum-instruction-assessment system. Although not a focus of this book, developing students' literacy skills as writers who can clearly and creatively communicate their evolving understanding of science is equally important (e.g., Harris Freedman 1999; Klentschy 2010; Norton-Meier et al. 2008).

Section 3. Integrated Instructional Mini Units: 5E Teaching Cycles

This final section is designed to reintroduce and provide models of 5E Teaching Cycles that integrate CIA. Appendix B in *Brain-Powered Science* (O'Brien 2010) gave an overview of this powerful CIA model that was developed by Biological Sciences Curriculum Study (BSCS) in the late 1980s as an expanded version of the 1970s Science Curriculum Improvement Study's (SCIS) learning cycle. Readers who have not read *Brain-Powered Science* are encouraged to download a synopsis from the model's original designers (Bybee et al. 2006) or simply study the sample activities in this section. The 5E Teaching Cycle of Engage, Explore, Explain, Elaborate, and Evaluate can be used at multiple levels of CIA design, from an individual lesson to a mini unit of a couple of days to a longer unit of between one and four weeks. Though individual lessons can be framed loosely in terms of this sequence, the model takes on its greatest power when used at the longer unit level, which includes an intentional, varied sequence of different kinds of instructional activities spread out over time. Given the purposes and space limitations of this book, the 5E mini units in this final section model the intermediate level of an instructional block of between several days and a week.

Section 3 has a stronger emphasis on big-picture biological, Earth, and space science concepts than any other section in the three-book series. Each 5E mini unit (activities #6–#13) includes several distinct but intentionally sequenced linked activities, and as a result each unit is longer than most other activities in the series. However, it is important to clarify what these 5E mini units are not. Specifically, they are not designed as comprehensive, ready-to-implement curriculum units with detailed daily lesson plans, student reading materials, and handouts. Commercial, grade-level-specific science textbooks typically come bundled as seemingly teacher-proof packages. Such packages can be quite useful if designed properly, but even the best of such packages need to be adapted, implemented, and revised "on the front lines in the trenches" of individual classrooms, where professional teachers make informed decisions about how to best serve their own students.

The purpose of these 5E mini units is to serve as a professional development tool to catalyze teachers toward CIA best practices as informed by cognitive science research. To achieve this objective, each 5E mini unit is explicitly linked to one or more of the big ideas in science (i.e., AAAS *Benchmarks* common themes of system, models, constancy and change, and scale; see Appendix C). Cognitive learning theories emphasize learning and teaching as linked processes of minds-on construction of new and improved mental schema scaffolded by the interactions between teacher and student, student and engaging phenomena, and student and student. As such, any individual discrepant-event activity (or 5E mini unit)—although useful as a lesson (or unit) "idea starter" to teach a particular science concept (or interrelated set of concepts)—has a broader purpose as a *visual participatory analogy* to help teachers rethink and refine other activities and units that are already part of their practice. Teachers learning how to teach science and teachers teaching students how to learn science are iterative and integrated, career-long processes. These mini units attempt to present teachers with a way of synergistically sequencing a series of engaging lessons where the whole is greater than the sum of the parts. As this is one of the take-home messages of this book series, it is appropriate to end this book by focusing on how discrepant events can be combined and sequenced into the 5E model of CIA.

Appendixes

Appendix A: ABCs of Minds-on Science Teaching (MOST) Instructional Strategies

Although inquiry-oriented discrepant-event and analogy-based activities are the primary foci of this book series, a variety of other strategies are modeled as well. Appendix A includes an extensive list of instructional approaches that can be incorporated into interactive, research-informed science curriculum-instruction-assessment (CIA). Individual teachers or groups of teachers are invited to see how many A-to-Z activities they can generate by brainstorming, then compare their list to the strategies they regularly use, with an eye to

- expanding their teaching repertoire to better "reach and teach" their diverse student populations by gaining and maintaining their attention, cooperation, and active minds-on participation; and

- supporting their own continued FUNdaMENTAL growth as lifelong learners of the science and improvisational art of science teaching (Tauber and Sargent Mester 2007).

An accompanying visual features the interaction effects of hands-on/hands-off and minds-on/minds-off learning and teaching.

Appendix B: An Integrated, "Intelligent" Curriculum-Instruction-Assessment (CIA) System

Research and policy statements on science education emphasize that a systems view of curriculum-instruction-assessment (CIA) is needed to close the gap between teaching efforts and learning results as measured on student assessments (NRC 2001b, 2001c, 2006). A Venn diagram is provided to help visualize the two-way interactions between these three interrelated components of effective teaching. The 5E Teaching Cycle is one approach to such an integrated CIA design.

Appendix C: Big Ideas in Science: A Comparison Across Science Standards Documents

This three-column table shows how the *Benchmarks for Science Literacy* (AAAS 1993), *National Science Education Standards* (NRC 1996), and *A Framework for Science Education: Preliminary Public Draft* (NRC 2010a) terminology for the big-picture ("forest") ideas of science align. All three documents emphasize the need to teach these ideas explicitly to contextualize the many individual "trees" of science and thereby promote understanding, retention, application, and transfer of scientific concepts over time. This book series provides a rich experiential context for teachers to learn how to incorporate these themes. Section 3 in this volume explicitly models how to teach for these big ideas across multiday instructional sequences.

Appendix D: Science Content Topics

This appendix (in conjunction with the index) can be used to help locate activities by the featured science content.

Activity Format (For New Readers)

As with the previous two *Brain-Powered Science* books, each dual-purpose science discrepant event/science education professional-development activity has the following standard format: Title, Expected Outcome, Science Concepts, Science Education Concepts, Materials, Points to Ponder, Procedure, Debriefing, Extensions, Internet Connections, and Answers to Questions in

Procedure and Debriefing. Many readers will be familiar with this format from the previous books, and new readers can probably understand the format from the headings or by working through one activity, so only a few comments are necessary here. Given this book's focus on encouraging teachers to be learners by directly experiencing "cognitive conflict" (Baddock and Bucat 2008; Chinn and Brewer 1993, 1998), the brief Expected Outcome statement and the relatively short explanations of the Science and Science Education Concepts do not need to be read *before* attempting a given activity. Scaffolded inquiry questions embedded in the Procedure and subsequent Debriefing questions are designed to help teacher-users discover the gist of the underlying ideas by doing the activity and reflecting on the results. Though these questions should also prove helpful when using the activities with grades 5–12 students, they are not intended as "teacher-proof scripts" to be followed. Instead, they should model and catalyze questions that the teachers-as-learners and their students will generate as they interact with the discrepant phenomena. Learner-generated questions are critical to learning as they reflect interest and cognitive engagement and provide formative feedback to both the teachers and the learners themselves (Chin and Osborne 2008).

The Answers to Questions in Procedure and Debriefing are intentionally placed at the end of each activity to encourage teachers to approach their own professional development as an inquiry-oriented, discover-the-answers versus read-the-answers activity. Encountering new activities from the perspective of a learner who doesn't know the answers ahead of time gives teachers valuable insights into the perspective of their own students. In particular, "miss-takes" often highlight science misconceptions that, if not directly confronted, have the power to derail the conceptual change process required in learning (Driver, Guesne, and Tiberghein 1985; Driver et al. 1994; Duit 2009; Fensham, Gunstone, and White 1994; Fisher and Lipson 1986; Harvard Smithsonian Center/MOSART; Kind 2004; Meaningful Learning Research Group; O'Brien 2011, Appendix A; Olenick 2008; Operation Physics; Osborne and Freyberg 1985; Posner et al. 1982; Science Hobbyist; Stepans 1994; Taber 2002; Treagust, Duit, and Fraser 1996; White and Gunstone 1992). Activating, challenging, and modifying or replacing seemingly valid misconceptions parallels the similar process that allows science itself to turn "promising, pregnant problems" (i.e., theory and evidence mismatch due to discrepant events) into the "birth" of new ideas and progress (Grant 2006; Youngson 1998).

Several additional format elements serve as catalysts for ongoing individual or group-based professional development that could continue for one or more years after initially experiencing the main activities as learners and testing them as teachers. The Extensions are brief descriptions of related inquiry activities that are useful for independent follow-up work by teachers as a means of formative self-assessment and to support the development of units that link a series of related activities (e.g., 5E Teaching Cycle–based units). The Internet Connections provide resources for teachers (e.g., professional development links, written descriptions, and Quick Time movies of similar or related discrepant-event demonstrations and computer simulations) that, like the Extensions, are starting points for further explorations. Given the continual flux of information on the internet, some links will change URLs or be dropped over time. However, most of the sites are hosted by universities, professional organizations, museums, online encyclopedias, science supply companies, and other such organizations or companies that tend to have a stable, long-term presence on the web. In addition to their inclusion in the text, these sites can be accessed electronically via an NSTA Press online, hyperlinked resource that will also allow for easy updating. E-learning experiences and resources are an ever-growing venue for teacher professional development and "just in time" instructional resources for teaching science across the K–16 range (NSTA 2008).

Most individual activities can be quickly modeled in 15–20 minutes when used with teachers as *science education visual participatory analogies* or as *model science inquiry lessons*. With instructional time so limited in most professional development settings, the activities are designed to be easy to set up, execute, and clean up. When used as science-inquiry activities with grades 5–12 students, the activities could take up to a full class period (or several days of instruction for section 3's 5E mini units) and would optimally be placed in an integrated instructional unit of related concepts and activities.

Closing Comment

This book series is based on the dynamic interplay between the philosophy of science, psychology of learning, and pedagogy of teaching as informed by the students, teachers, and researchers that I have had the pleasure and privilege of learning with and from during my nearly 50 years as a student and teacher. Being a teacher affords one the opportunity and responsibility to be a lifelong learner in a professional learning community that both "stands on the shoulders of giants" (i.e., previous scientists, philosophers, and educators) and lifts up the next generation to see farther and travel farther. With deep gratitude to the past, the *Brain-Powered Science* series reframes a collection of classic and newer science discrepant events as dual-purpose science inquiry lesson examples—analogies for science teacher education. The objective of this somewhat unique pairing is that teacher-readers can learn from minds-on reflection in and on the same FUNdaMENTAL science experiences they can subsequently use to Engage, Explore, Explain, Elaborate, and Evaluate their own grades 5–12 students. As such, the activities should be dissected and reconstructed by teachers in the cauldrons of classrooms. (*Note:* The generous amount of white space in the books is there for your comments, corrections, connections, and next-step extensions.)

My intention is to provide "food for thought" for individual classroom teachers and teacher educators. However, good food tastes even better when shared. Just as progress in science depends on collaboration across individual laboratories within scientific communities, educational progress requires that teachers share both their successes and "miss-takes" (i.e., lessons learned and/or problems identified) with each other within and across science departments, school districts, and electronically linked professional science education associations. Schools will achieve their potential as learning organizations when teachers are learning as much as students, and when teachers leave such schools, they leave behind stronger, smarter organizations that are prepared to identify and resolve new, interesting, and important problems. Our country and world demand and deserve nothing less than truly progressive education. As John Dewey (1938) so eloquently put it in *Experience and Education*:

> The belief that all genuine education comes about through experience does not mean that all experiences are genuinely or equally educative. Experience and education cannot be directly equated to each other. For some experiences are mis-educative (p. 25) ... Wholly independent of desire or intent, every experience lives on in further experiences. Hence the central problem of an education based upon experience is to select the kind of present experiences that live fruitfully and creatively in subsequent experiences (pp. 27–28) … Unless a given experience leads out into a field previously unfamiliar no problems arise, while problems are the stimulus to thinking … growth depends upon the presence of difficulty to be overcome by the exercise of intelligence … it is part of the educator's responsibility to see ... The new facts and new ideas thus obtained become the ground for further experiences in which new problems are presented. The process is a continuous spiral. (p. 79)

Science Education Topics

As with the two previous books, this book has two foci—*discrepant-event science inquiry activities* and linked *visual participatory analogies for science teacher education*. The following topics are organized to show the sequence of sections by the larger frame science education themes. Appendix D lists the science concepts in alphabetical order. In either case, the book does not need to be used in any kind of strict linear sequence, but rather can be explored on a "need to know and use" basis.

Acronyms Used in Science Education Topics

BBS: Black Box System: A hidden mechanism is explored via observation and testable inferences.

BIO: Biological analogies and applications are specifically highlighted.

HOE: Hands-On Exploration: Learners working alone or in groups directly manipulate materials.

HOS: History of Science: A story, case study, or resource from the history of science is featured.

MIX: Mixer: Learners assemble themselves into small groups based on a specific task.

NOS: Nature Of Science: These activities focus on empirical evidence, logical argument, and skeptical review.

PAD: Participant-Assisted Demonstration: One or more learners physically assist the teacher.

POE: Predict-Observe-Explain: These activities use this inquiry-based instructional sequence.

PPP: Paper-and-Pencil Puzzle: These activities use a puzzle, which is typically focused on the NOS; often a BBS.

STS: Science-Technology-Society: The focus is on practical, real-world applications and societal issues.

TD: Teacher Demonstration: The teacher manipulates a system and asks and invites inquiry questions.

TOYS: Terrific Observations and Yearnings for Science: The activity uses a toy to teach science.

Science Education Topics

Section 1. Welcome Back to Interactive Teaching and Experiential Participatory Learning

Activity	Activity Type	Science Concepts
1. Science and Art: Dueling Disciplines or Dynamic Duo?	PPP/MIX TD optional p. 3	NOS as compared to art diffraction of white light to form a rainbow of colors Extensions: Draw-a-Scientist-Test + Science for All Americans + HOS
2. Acronyms and Acrostics Articulate Attributes of Science (and Science Teaching)	PPP TD optional p. 21	NOS, teaching, and mnemonics acid-base indicators and pH Extensions: Analyzing Assumptions About Learning-Teaching

Section 2. Reading, Student Construction of Meaning, and Inquiry-Oriented Science Instruction

Activity	Activity Type	Science Concepts and Learning Principle Modeled
3. Tackling the Terrible Tyranny of Terminology: Divide and Conquer	PPP TD options p. 37	reading, cognition, and NOS acid-based indicators and/or pressure-volume lung model
4. Inquiring Into Reading as Meaning-Making: Do Spelling and Punctuation Really Matter?	PPP p. 51	reading, cognition, NOS, and POE Extension: Cloze test and inference-making
5. Ambiguous Text: Meaning-Making in Reading and Science	PPP p. 63	prior knowledge, reading, and cognition: empirical evidence, logical argument, and skeptical review in science and reading Extension: Fossil Footprints

Section 3. Integrated Instructional Mini Units: 5E Teaching Cycles

Safety Practices

The discrepant-event, inquiry-based experiments in this book include teacher demonstrations, participant-assisted demonstrations, paper-and-pencil puzzles, and student hands-on explorations. In all cases, it is essential that teachers model and monitor proper safety procedures and equipment and teach students pertinent safety practices through both words and actions. Though the hands-on experiments typically only use everyday materials and household, consumer-type chemicals (e.g., water, sugar, salt, ammonia, and rubbing alcohol), teachers should consider their students' ages and particular teaching environments when deciding how to use particular activities and which safety precautions are necessary. Professional prudence, preparation, and practice greatly reduce the probability of accidents. Effective classroom management and safety are non-negotiable components of effective science teaching even when using very low-risk activities such as those featured in this book. Beyond these activities, consider incorporating the following best-practice safety precautions into your science teaching.

1. Always review Material Safety Data Sheets (MSDS) with students relative to safety precautions in working with hazardous materials. Chemicals purchased from science supply companies come with MSDS. These are also available from various online sites (e.g., *www.flinnsci.com/search_msds.asp*).
2. Wear protective gloves and aprons (vinyl) when working with hazardous chemicals.
3. Wear indirectly vented chemical-splash goggles when working with potentially hazardous liquids or gases. When working with solids such as soil, metersticks, glassware, and so on, safety glasses or goggles can be worn.
4. Do not eat or drink anything when working in a laboratory setting.

5. Consider student allergies and medical conditions (e.g., latex, peanut butter, and asthma) when using activities that could elicit a negative response.
6. Wash hands with soap and water after doing the activities dealing with hazardous chemicals or other materials.
7. When working with volatile liquids, heating or burning materials, or creating flammable vapors, make sure the ventilation system can accommodate the hazard. Otherwise, use a fume hood.
8. Immediately wipe up any liquid spills on the floor—they are slip-and-fall hazards.
9. Teach students that the term *chemical* is not synonymous with *toxic*, that *natural* is not synonymous with *healthy and safe*, and that chemicals they encounter on a daily basis outside of the science lab should be used in an informed manner. Scientifically literate citizens and consumers steer between the extremes of chemophobia and careless use of chemicals.
10. Science teachers should stay current on safety threats, environmental risks, and appropriate precautions as part of their ongoing, career-long professional development (Flinn Scientific; Kwan and Texley 2003; Texley, Kwan, and Summers 2004).

References

Council of State Science Supervisors (CSSS). Science Safety Guides (free downloads): *www.csss-science.org/safety.shtml*.

Flinn Scientific, Inc. Safety resources: *www.flinnsci.com/Sections/Safety/safety.asp*.

Kwan, T., and J. Texley. 2003. *Exploring safely: A guide for middle school teachers.* Arlington, VA: NSTA Press.

Texley, J., T. Kwan, and J. Summers. 2004. *Exploring safely: A guide for high school teachers.* Arlington, VA: NSTA Press.

U.S. Department of Health and Human Services: Household Products Database: *http://householdproducts.nlm.nih.gov*.

Activity 10

Osmosis and "Naked" Eggs

The Environment Matters

Expected Outcome

Fresh, uncooked, de-shelled eggs (i.e., eggs previously placed in an acid bath) are observed to increase in volume when placed in water or to decrease in size when placed in corn syrup. This macroscopic model of osmosis can be used as an introduction to the evolution of eukaryotes and multicellularity as a means to grow beyond the size limitations of very small, microscopic prokaryotic cells.

Science Concepts

Osmosis is the diffusion of water through a selectively permeable membrane. It is a form of passive cellular transport (i.e., it doesn't "cost" the cell energy) where water moves from a region of higher water concentration to a region of lower water concentration (until a dynamic equilibrium is reached when the water concentrations are equal). Unfertilized, haploid mammal and bird eggs (or just-fertilized, diploid ones before they start to divide and differentiate) are unusually large, macroscopic single cells. The human egg is about the size of a period and bird eggs can be as large as an ostrich's egg; in both cases, the embryo itself is initially a very small part of the egg's total volume, which is primarily food. An egg's shell must be able to contain the vital liquid water content of the egg, yet porous enough to allow oxygen used in the growing embryo's metabolic processes to enter and to release the carbon dioxide that is produced as a result. A soft, flexible cell membrane lies just beneath the hard exterior shell of the egg. Given their size and availability, unfertilized chicken eggs provide a convenient macro-*scale model* of the *system*-level phenomenon of osmosis (as driven by invisible molecules-in-motion).

Once the shell of a fresh, uncooked chicken egg is removed in an acid bath, the egg's intact, selectively permeable cell membrane is elastic enough to noticeably swell and shrink without bursting in response to changing osmotic pressure. Random movements of relatively smaller, faster-moving water molecules cause the net flow of water to move from the side of the membrane where they are more concentrated to the side where they are less concentrated. Egg white is about 90% water and corn syrup is about 25% water. Thus, if a de-shelled egg is placed in corn syrup, water moves from inside the egg to outside the egg, leaving the egg shrunken and limp (versus the de-shelled egg placed in pure water, which swells and tightens). As such, the de-shelled egg-solution system demonstrates how *constancy and change* (i.e., dynamic equilibrium) define biological systems.

Students are likely to have a variety of misconceptions and conceptual "holes" related to this mini unit, including the following:

1. All cells are microscopic.
2. Macroscopic, unfertilized, grocery store chicken eggs were either never alive or are made of many now-dead cells that do not display any of the characteristic processes of living cells.
3. Shells in bird eggs and cell walls in bacteria and plant cells are substitutes or replacements for cell membranes (which unfortunately sometimes are not clearly highlighted on textbook visuals).
4. Diffusion-related concentration gradients always cause the movement of the solute, not the solvent. Students are also unlikely to differentiate osmosis from active transport that enables cells to preferentially maintain higher unique combinations of various biomolecules and ionic concentrations inside (versus outside) the cell. This capability is what distinguishes living cells from their external environments. Clarifying these misconceptions also allows osmosis to be used as a lead-in to an Elaboration-phase analysis of cell surface-area-to-volume restrictions and the evolution of membrane-bound cellular organelles and multicellularity (in eukaryotes) from simpler, single-celled prokaryotes.

If desired, the corrosive effect of an acid on calcium carbonate can also be discussed as a visual analogy for acid rain's effect on marble and limestone, which are also forms of $CaCO_3$.

Science Education Concepts

As a *visual participatory analogy*, students' minds can be viewed as selectively permeable membrane-bound systems that allow certain inputs and outputs (and reject or restrict others) that vary with the particular curriculum-instruction-assessment (CIA) environment in which the students are placed. Intelligently designed CIA environments facilitate a "loss" of misconceptions, a "gain" of scientifically valid conceptions, and an overall expansion of understanding and capacity for future learning. Poorly designed CIA environments cause students' minds to "shrink" in capacity for future learning (i.e., are mis-educative). Of course, a critical limitation of this analogy is that learning is not a form of passive transport or "absorption" of static external facts, but the learner-active, energy-requiring construction of new and reconstruction of old conceptual schemas in light of new experiences via assimilation and accommodation. 5E Teaching Cycles (Engage, Explore, Explain, Elaborate, Evaluate) are designed to scaffold learning across a planned, logical, dynamic sequence of student-teacher, student-student, and student-phenomena interactions.

Materials

Safety Note

Raw eggs can carry salmonella, so be sure to wear disposable plastic gloves (if available) and wash hands with soap after handling the raw, de-shelled eggs. Students should be warned to avoid touching their eyes, nose, and mouth, as they are potential entry points for bacteria. If desired, the science of transmission of this enterobacteria species of bacteria may be included in this lesson sequence. See Internet Connections: Salmonella.

- For a teacher demonstration, 4 fresh, uncooked eggs are needed. If done as a hands-on exploration, a dozen (12) eggs for a class would allow 2 eggs for each of 6 groups of 4 students.
- For each egg, you will need about 250 ml of vinegar (dilute acetic acid), 250 ml of colorless corn syrup, and a 500 ml glass beaker with a piece of aluminum foil and rubber band or plastic wrap to control odor (or alternatively, 16–18 oz. plastic, sealable jars).
- Measuring tape (or string and a metric ruler) and an optional balance are needed to measure pre- to postosmotic changes in size and mass.
- A colander or screen serves as a macroscopic model that allows small particles (e.g., sand or BBs) to pass through, but not larger ones (marbles). The use of a plastic zip-top bag, tincture of iodine solution, and (corn)starch solution serves as another model system.
- Several boxes of sugar cubes or a box of 1 cm^3 mathematics cubes (for a HOE) and/or several shoe boxes (for a demonstration) are also needed.
- Cubes of raw potato or gelatin, acid-base indicators, vinegar or dilute (0.1–0.4%) sodium hydroxide, and a soap bubble solution are needed for optional elaboration phase activities.

Time note: For use as a demonstration when working with teachers, prepare de-shelled eggs and then immerse them in water or corn syrup solutions for several days prior to class. About 20 minutes of discussion time is needed to quickly take teachers through the first three phases of a modified 5E Teaching Cycle. A variety of biological demonstrations require this TV cooking-show-type advance preparation (e.g., Bilash and Shields 2001; Ingram 2003; VanCleave 1989, 1990, 1991a, 1991b).

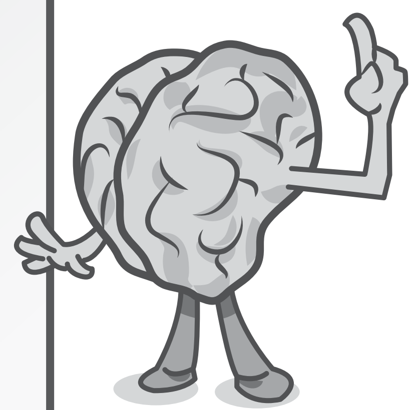
Points to Ponder

Contact with things and laboratory exercises, while a great improvement upon textbooks arranged upon the deductive plan, do not of themselves suffice to meet the need. While they are an indispensable portion of the scientific method, they do not as a matter of course constitute scientific method. Physical materials may be manipulated with scientific apparatus, but the materials may be disassociated in themselves and in the ways in which they are handled, from the materials and processes used out of school … There is sometimes a ritual of laboratory instruction as of heathen religion.

—John Dewey, American philosopher-educator (1859–1952) in his 1916 book *Democracy and Education* (see Internet Connections)

… learning is a dual process in which, initially the inside beliefs and understandings must come out, and only then can something outside get in. It is not that prior knowledge must be expelled to make room for its successors. Instead these two processes—the inside-out and the outside-in movements of knowledge—alternate almost endlessly. To prompt learning, you've got to begin the process of going from the inside out. The first influence on new learning is not what teachers do pedagogically but the learning that's already inside the learner.

—Lee Shulman, "Taking Learning Seriously," *Change* 31 (4): 10–17.



Procedure

This 5E sequence can be completed as a demonstration-experiment (with teachers in a cut-time frame) or as a lengthier series of hands-on exploration (with grades 5–12 students).

Engage: Macroscopic Models and Egg-citement About Cells

1. If used as a Teacher Demonstration: Between two and four days prior to beginning the activity, use a tape measure to determine the vertical and horizontal "circumferences" of four fresh, uncooked eggs. Submerge the eggs in vinegar. The weak, dilute acetic acid in the vinegar (i.e., approximately 5% acid and 95% water) will chemically react with the calcium carbonate in the egg's shell to form water-soluble calcium acetate, carbon dioxide gas (bubbles), and water. If the shells are not completely removed in 24 hours, replace the used, reacted vinegar with fresh vinegar and let the eggs soak for another 24 hours. After the shells are completely gone, rinse two of the three de-shelled, translucent eggs with water, re-measure their circumferences, weigh them, and submerge one in colorless corn syrup and the other in water (leave the third in the vinegar). Within a day, the first egg will lose water to the corn syrup and dramatically shrink in size and mass, and the second one will gain water from its water bath (the third left in vinegar should remain fairly constant). The changes can be measured and tabulated over a one to four day period. Be sure to cover the beakers or use sealable jars to control odor.
2. On the day of the demonstration, introduce this mini unit by briefly highlighting some key historical events. In 1665, Robert Hooke, an English scientist who developed some of the earliest compound microscopes, coined the term *cells* to describe the walled, empty chambers he observed in slices of cork at 30× magnification that reminded him of the cells in monasteries. His contemporary, a Dutchman amateur scientist named Antonie van Leeuwenhoek, was simultaneously discovering a wide variety of what we now know to be living, motile, single-celled organisms everywhere he looked with his 10-times-more-powerful single-lens microscopes. Improvements in microscopy led to discoveries of increasingly varied and ubiquitous

cells in and on macroscopic living creatures and on land and in water. Nearly two centuries later, in the late 1830s, a German physiologist-anatomist (Theodore Schwann) and botanist (Matthias Schleiden) both wondered if cells were the biological equivalent of chemists' atoms (as proposed by John Dalton in 1808). That is, were cells the basic unit of all life? Let's explore this and related questions:

a. Are all living things composed of cells? Are all cells microscopic? Hold up a fresh, raw egg and ask: Can a chicken egg bought in a grocery store be considered a single large cell?
b. What is the most basic and universal component of every living cell (from the smallest and simplest prokaryotic to the largest or most complex eukaryotic cell) and what is this structure's function?
c. Do chicken eggs have a cell membrane? Is it the same as the shell?
d. Is there a way to remove the shell of a fresh, uncooked egg (without hard-boiling it!) and still have the egg maintain its shape and contents? What is the main chemical ingredient of eggshells? What liquids might chemically react with and dissolve this chemical compound?

    Optional Teacher Demonstrations: Place a fresh egg, eggshell, or a piece of white chalk in a hardware-store-bought solution of muriatic acid (HCl sold as a masonry cleaner) or laboratory hydrochloric acid (the more concentrated, the faster the reaction). This is much quicker and more dramatic than using the more dilute and weak acetic acid found in vinegar. Alternatively, you may wish to contrast the effectiveness and speed at which "Easter egg" color-dyeing occurs with versus without the recommended vinegar solution. In either case, the demonstrations can be reserved for a postlab activity that leads into the STS issue of acid rain.

e. *If the activity is to be done as an HOE:* Have learner teams measure the circumferences of their two raw eggs and place them in vinegar in sealed jars for a lab that will resume in a day or two after the de-shelling. If done as a demonstration, proceed directly to the Explore phase.

Safety Note

Wear indirectly vented chemical-splash goggles.

Explore: Eggs-perimental Science: If used as a Teacher Demonstration:

3. a. Tell the learners you have previously removed the eggshells from two eggs in a similar (but slower) fashion than in step #2d and that you would like them to examine the results. Distribute for up-close inspection (or use a projection video camera to display the image of) two de-shelled, "naked" eggs that have been soaking in vinegar. If disposable plastic gloves or soap and water are available for subsequent hand cleaning, allow the learners to hold a de-shelled egg in their hands to feel the osmotic pressure. Alternatively, the de-shelled eggs can be placed in zip-top bags before allowing the students to handle them without risking the mess of a ruptured egg. Also, the inside yolk can be more readily noticed when the room is darkened and a flashlight beam is held against the egg. Draw attention to the thin, translucent, flexible cell membrane that is still keeping the egg's contents inside. Ask the learners: What everyday material does the cell membrane reminds you of? Do you think certain kinds of materials could pass through the cell membrane without rupturing it? How might you test if a cell membrane is "permeable"? What kind of materials would need to pass through an egg's cell membrane (and the egg itself) if the egg had been fertilized and contained a developing embryo? Why?

   b. Display or circulate the two other de-shelled eggs. As they examine the one that has been soaking in water and the other in corn syrup for 1–3 days, ask: What is the main chemical component of the interior of eggs? How could we test whether movement of water is occurring through the membrane?

   c. Lead the learners to see that the egg's cell membrane allowed water to enter into the egg in the case of the water bath and water to leave the egg in the corn syrup solution.

   d. *Optional Teacher Demonstration*: The Steve Spangler Science website (How to Make a Folding Egg) describes a classic magician trick that relies on an "empty" egg cell membrane made by poking two small holes on opposite ends of a fresh, clean egg and shaking the egg to "scramble" the contents, which are then removed by blowing on one end of the egg before soaking it in an acid to remove the shell. The empty cell membrane can be used to demonstrate the thinness of the cell membrane.

If the activity is to be done as an HOE, steps #3 a–c would be developed collaboratively with students as a part of a discussion on experimental design.

Explain: Just Passing Through: Modeling the (w)Hole Truth About Osmosis

After the data have been tabulated and the learners have been challenged to use logical arguments and skeptical review to explain the empirical results, demonstrate the following two macroscopic models of the molecular level process.

Part 1: Colanders Count (and Sort by Size): Use a colander or screen as a physical model to demonstrate a semipermeable or selectively permeable membrane that "selects" for small molecules by "sifting and sorting" a mixture of marbles and BBs or BBs and sand. Ask:

4. a. If the colander or screen represents the cell membrane, what property of molecules is it "selecting for"?
   b. Which size particles in this model represent water and which ones represent sugars, proteins, and other biomolecular components of the cell?
   c. Because the smaller particles can pass either way through the colander, what factor determines which way they move in this model? How is this different than a real cell membrane?
   d. Rather than a gravity gradient, what factors determines the direction of water molecules in our egg cell model? Why is two-way movement important for cells?

Part 2: Plastic Baggie Membrane Model: Demonstrate that drugstore tincture of iodine (I_2 dissolved in alcohol) or Lugol's solution (I_2 dissolved in an aqueous solution of KI) turns a dark blue-purple in the presence of starch and thus serves as a chemical indicator for this large polysaccharide (but not for mono- or disaccharides). Use a zip-top bag as a model of the cell membrane. Place a starch solution (e.g., cornstarch, diced potatoes, or eco-foam or starch packing peanuts dissolved in water) on the inside of the bag, being careful to not spill any on the outside. Then push out any air, seal the bag, and rinse the outside with water. Place the sealed bag into a beaker that contains a dilute tincture of iodine or an I_2-KI solution. Prepare a comparable setup with the location of the two solutions reversed. Ask students to predict-observe-explain what will occur in the two setups. Challenge them to make drawings that depict relative sizes and concentrations of the various components of this system prior to showing dynamic macroscopic simulations and/or computer animations (see below). *Note:* I_2 is a comparatively small molecule and starch is a quite large molecule, $(C_6H_{10}O_5)_n$. The relatively large starch molecules cannot diffuse through the smaller intermolecular "holes" in the plastic membrane, but the smaller iodine molecules can. In *Brain-Powered Science*, Activity #20, Extensions #2 and #3 (pp. 217–218) describe a soap bubble–cell membrane analogy and the diffusion of vanilla through a sealed, inflated balloon; see also the Access Excellence and Nanopedia websites in Internet Connections.

Part 3: Simulating the Sorting Sequence: See the Internet Connections for a number of excellent molecular simulations on diffusion and osmosis. Computer animations and/or people-as-molecules simulations are powerful means of helping students visualize molecular motions and mechanisms that are otherwise unseen and difficult for students to appreciate. Learners can also explore other systems that demonstrate osmosis, such as those that use dialysis tubing.

Reading selections from the textbook and internet sources (especially those with animations) can be used to supplement the class discussions. Be sure to feature the "big ideas" of systems, models, constancy and change, and scale (see Appendix C). Also, live, projected microscopy or multimedia clips can be used to challenge students to predict-observe-explain what happens to living cells when they are placed in hypertonic, isotonic, and hypotonic solutions.

Elaborate:

Part 1: How Sweet It Is to Have a Large Surface-Area-to-Volume Ratio: Return to these questions: Why are nearly all cells limited in size to the microscopic realm? Why don't we observe lots of macroscopic unicellular organisms (as commonly featured in science cartoons; see the Science Cartoons Plus website in Internet Connections)? How does the size of a cell influence its ability to exchange materials (e.g., water, nutrients, and waste products) with its environment through osmosis (as well as via active transport)? Despite textbook pictures and views through standard microscopes that suggest otherwise, all cells are 3D, not 2D. As a cell increases in size (volume, or V), does it increase proportionally in surface area (SA)?

Teacher Demonstration

Use identical shoe boxes to construct model cells that are made up of one, two, three, and four boxes. Make a quick qualitative argument about the loss of effective (exposed) surface-area-per-unit volume when the boxes are stacked on top of (and/or alongside) each other.

Student Hands-on Explorations

Distribute variable numbers of 1 cm^3 math blocks (or use sugar cubes as a somewhat larger substitute) to teams of students to construct 3D cubes of increasing linear dimensions (i.e., 1 cm × 1 cm × 1 cm [1 block], 2 cm × 2 cm × 2 cm [8 blocks], 5 cm × 5 cm × 5 cm [125 blocks]). Have each team build and calculate the surface area (SA) and volume (V) for two different-size cubes. *Note:* For a cube, SA = $6s^2$ and V = s^3 where s = length of a side. Alternatively, rather than using blocks as cells, use water-filled zip-top bags. Students can measure the surface areas of different-size zip-top bags (up to the seal), then measure what volume of water is needed to fill them. In either case, collectively tabulate and share the data to reveal that the SA/V ratio (= $6s^2/ s^3 = 6/s$ for cubes) decreases dramatically as the overall size increases because surface area increases by the square and volume by the cube of the linear dimension. Cells that grow "too large" would suffer from limited access to nutrients and oxygen and an inability to rid themselves of their own metabolic waste products! Similarly, because mass is proportional to volume for a given substance with a given density (e.g., 1 cm^3 of water weighs 1 g), the mass of the cubes also increases faster than the surface area, which makes issues of structural support a problem for nonaquatic organisms.

If desired, challenge the learners to develop an experiment that uses biological material to empirically verify the logic of the mathematics of surface-area-to-volume ratios. *Idea starter:* A raw potato can be cut into cubes of increasing size, submerged in a dilute tincture of iodine solution for a period of time, and subsequently dissected to compare how far into the different potato cubes the iodine solution (an indicator that turns a dark blue-purple in the presence of starch) penetrated. Alternatively, different-size agar or uncolored gelatin cubes can be made with an acid-base indicator (e.g., phenolphthalein or bromthymol blue) dissolved in them. When placed in the appropriate solution (e.g., 0.1–0.4% sodium hydroxide or vinegar, respectively), the solution will diffuse into the cube's interiors (and effect a color change) at a depth related to the surface-area-to-volume ratio of the cubes. Versions of these labs are sold by science supply companies and appear on the web. Again, online simulations (Internet Connections) can be used to complement the macroscopic models.

Part 2: Life Invents Bigger Cells and Multicellularity to Move From the Micro to Macro Worlds: Typical prokaryotic cells (bacteria) are 1–10 $\times 10^{-6}$ m in length (or diameter), as compared to typical eukaryotic cells that are 10–100 $\times 10^{-6}$ m. These differences in linear dimensions of 10–100 translate to factors of 1,000–1,000,000 in volume differences between the two types of cells (see *More Brain-Powered Science*, Activity #17, Extension #1). This raises questions such as the following:

- Why are nearly all cells microscopic?
- How do eukaryotic cells bypass the limits that seem to restrict bacterial cell size?
- What did nature "invent" to get around the size limits of unicellular eukaryotes?

Optional Soap Bubble Membrane Model: Commercial or homemade soap bubble solutions can be used to model the membrane-bound organelles of eukaryotes. Blow a large semispherical bubble on a wet sheet of overhead transparency; dip a straw into the bubble solution;

and insert the straw through the first bubble to blow a bubble within a bubble (to represent a membrane-bound nucleus) and withdraw the straw. It is also worth noting that a sphere is the 3D shape that has the smallest surface-area-to-volume ratio for a given volume. That is, it requires the least amount of material to "build" an enclosed space to contain a certain volume of material. Have the learners calculate the surface area of a square ($6s^2$) versus a sphere ($4\pi r^2$) of the same (arbitrary) volume and discuss why spherical cells would make "economic sense" for cells. Scale effects are important to life at all levels of organization. See Internet Connections: Access Excellence and/ or *Brain-Powered Science*, Activity #20, Extension #2.

Evaluate:

Learners could be challenged to apply and explain the science of osmosis as related to real-world applications such as the following:

a. Few aquatic species are adapted to inhabit both freshwater and saltwater environments.
b. Contact lens cleaning solutions and intravenous (IV) solutions need to be isotonic with the patient's eye or bloodstream.
c. Shipwrecked sailors should not drink salt water because it is hypertonic relative to their cells.
d. Road salt used for de-icing poses a problem for plants and animals that live in the soil near the road.
e. Fresh vegetables can be kept crisper in grocery stores if they are periodically sprayed with a water mist or, when taken home, soaked in water or placed in a more moist section of a refrigerator or in sealed plastic bags.

Learners could be asked to predict-observe-explain the outcomes of any number of other demonstrations and experiments described in various books and biology education websites that relate to osmosis and/or surface-area-to-volume scale effects (e.g., the functioning of kidney, the small intestines, and the lungs). See Internet Connections as a starting point.

Debriefing

When Working With Teachers

Discuss the positive and negative attributes of the de-shelled egg as a visual participatory analogy for a student learner and how it relates to Shulman's quote with its emphasis on the dynamic interaction between "the inside and outside" (see also *Brain-Powered Science*, Activities #11, "Super-Absorbant Polymers," and #20, "Needle Through the Balloon"). Clearly, the CIA environment does make a difference in terms of student cognitive gains! The 5E Teaching Cycle offers multiple and different kinds of learning opportunities for students to build a solid conceptual understanding of a given topic. Also, challenge the teachers to consider the relevance of John Dewey's assessment of conventional laboratory "exercises" in the Points to Ponder quotes. Teachers may want to read and discuss a more recent critique of standard laboratory "exercises" (Singer, Hilton, and Schweingruber 2006; see Internet Connections: *America's Lab Report*).

As time permits and need requires, review the science of osmosis and discuss how the demonstration version could be modified for a direct hands-on exploration (HOE) (e.g., quantitative measurements of the changing mass and circumference of the eggs over a three to five day time period, including attempts to reverse the process for both swollen and shrunken eggs). Several versions of related labs and demonstrations exist on the internet.

When Working With Students

When used as either a demonstration and/or an HOE, this 5E mini unit fits into a larger unit on cells. A key factor in explaining osmosis is getting students to focus on the concentration of the solvent, water (in a water solution), when they more commonly focus on the opposite, the concentration of solutes in a water solution. Diffusion always involves movement down a concentration gradient. In cells, water, oxygen, carbon dioxide, and glucose molecules are all small enough to diffuse through the intermolecular "holes" in cell membranes. A central task of every cell is to maintain homeostasis or internal *constancy* amidst external *changes* in its aqueous environment that has a very different overall chemical composition. The fact that the acid bath "eats" the hard eggshell but not the cell membrane can be used to emphasize the "tough but thin" nature of the cell membrane (though, in fact, most living cells would not survive such an acid bath, even if their cell membranes did).

Osmosis is only part of the story. Some single-celled organisms (e.g., *Paramecium*; see the Internet Connections for Activity #7) have specialized structures called water vacuoles to help with water balance. Also, cells are constantly exchanging other chemicals with their environments. The movement of these other chemicals (e.g., larger molecules and ions) involves active transport that requires cellular energy to work against simple, concentration-based diffusion gradients. The eukaryotic cell's invention of membrane-bound organelles can be introduced as a means of increasing surface-area-to-volume ratios for performing chemical reactions and exchanges within the cell. Bacteria, algae, fungi, and plants have their cell membranes within an outer, rigid cell wall that maintains the shape of the cell, provides physical protection, and prevents the cell from bursting in a hypotonic environment. The latter can be modeled by blowing up a balloon (cell membrane) within the foot of an old nylon stocking (cell wall). The stocking will cause the balloon to resist further expansion when "it is full." One way that antibiotics kill bacteria (but not viruses) is by preventing bacteria from forming functional cell walls. Cell walls do not protect against plasmolysis in a hypertonic solution; this explains the antibacterial properties of salted meats and the problem plants have with road salt (see Internet Connections: DarylScience).

If desired, the first part of the demonstration (i.e., the acid bath) can also be used in the Engage phase of a unit on the effects of acid rain on limestone and marble statues and buildings, as well as on wildlife. Rainwater is naturally slightly acidic due to the normal presence of carbon dioxide in our atmosphere. But industrial activity has caused pH levels to drop lower than 5 due to the large-scale burning of fossil fuels that produce carbon dioxide, sulfur oxides, and nitrogen oxides that combine with atmospheric moisture to produce "acid rain" that threatens plants and animals and increases corrosion of metals and buildings.

Extensions

See the Elaboration phase and the Internet Connections for a variety of biological activities related to osmosis. Alternatively, when working with teachers, emphasize the amazing number of science concepts that can be explored using low-cost, everyday materials such as eggs in FUNdaMENTAL ways. Consider the following Egg-citing Physical Science Egg-speriments:

1. *Egg in the Bottle Demonstrations:*
   a. The biology of osmosis can be used to reduce the size of an uncooked, de-shelled egg by first placing it in corn syrup; then, after the egg has shrunk, place it in the bottle; pour distilled water into the bottle to "grow" the shrunken egg back to its original size or larger; and, finally, pour the water out of the bottle to leave an enlarged egg in the bottle. The last step should be done immediately before the class enters the room.
   b. The physics or chemistry gas-law-related alternatives are much quicker. Place a de-shelled hard-boiled egg on a bottle that has just been filled halfway with hot water, shaken, then emptied. The mouth of the bottle should be just slightly smaller than the egg's diameter. As the hot air trapped in the "empty" bottle cools, the internal air pressure will drop relative to the external atmospheric pressure, which forces the egg into the bottle. An even quicker way of getting the egg into the bottle is to drop a burning piece of paper into an "empty" bottle, then place the de-shelled egg on top. Challenge students to use prior knowledge to suggest ways of removing the intact egg from the bottle (e.g., heat the bottom of an upside-down bottle). See also the Internet Connections: Steve Spangler Science for a variation that uses a water-filled balloon.
2. *Egg-on-End Magic Challenge*: Challenge students to stand a fresh, uncooked egg (in its shell) upright on its end. This can be done in various ways. Prior to your public (teacher-only) demonstration of this feat, repeatedly drop muriatic (HCl or hydrochloric) acid on the big end of the egg to dissolve just a small portion of the eggshell, exposing a soft area of the egg membrane. Your pretreated

egg will stand up on this presoftened end. Alternatively, vigorously shake a fresh egg to break the egg yolk "free from its moorings." When this slightly scrambled egg is placed on its end, the heavier yolk will sink down within the egg white, lowering the egg's center of gravity and stabilizing it. Without the benefit of a "trick," students will not be able to replicate this feat. The difference between magic and science is understanding the "why," and a teacher's goal is to promote science without destroying students' sense of wonder about the real magic of nature.

3. *Eggs-traordinary Fluoride Protection and Tough Teeth:* Smear fluoride toothpaste on the entire surface of an egg; let it sit for 24 hours, then wash it off with warm water. Compare the effects of a vinegar bath on this treated egg versus an untreated one. The fluoride ions react with the calcium ions in the shell and provide an acid-protective coating similar to the effect of protecting tooth enamel from acidic saliva and foods. This simple activity demonstrates how knowledge of biochemistry allows humans to live longer, healthier lives than our ancestors (who suffered greatly during their short lives from premature tooth decay and a host of other problems that modern science has solved).
4. *More Brain-Powered Science*, Activity #3, "Dual-Density Discrepancies," Extension #1: Egg-citing Egg-speriment
5. *Brain-Powered Science*, Activity #29, "Rattlebacks," explores egg spinning and rotational dynamics.

Internet Connections

- Access Excellence:

  Investigating Cell Sizes: *www.accessexcellence.org/AE/ATG/data/released/0239-AltonBiggs/index.html*

  The Cell Membrane and Surface Area Demos: *www.accessexcellence.org/AE/ATG/data/released/0307-TrumanHoltzclaw/index.html*

  Modeling Limits to Cell Size: *www.accessexcellence.org/AE/AEC/AEF/1996/deaver_cell.html*

Egg Osmometers: Teacher Notes: *www.accessexcellence.org/AE/ATG/data/released/0519-NancyIversen/index.html*

Diffusion and Osmosis: *www.accessexcellence.org/AE/ATG/data/released/0081-JeffLukens/description.html*

Using Bubbles to Explore Membranes: *www.accessexcellence.org/AE/AEC/AEF/1995/wardell_membranes.php*

- *America's Lab Report: Investigations in High School Science*: *www.nap.edu/catalog/11311.html*
- *BSCS 5E Instructional Model: Origins, Effectiveness and Applications*: *www.bscs.org/pdf/5EFull Report.pdf* (65 pages)
- Biology Corner: Cells (diffusion, osmosis, and more): *www.biologycorner.com/lesson-plans/cells*
- Cell Biology Animations: *www.johnkyrk.com*
- Cell-ebration Homepage: *www.usd.edu/%7Ebgoodman/Cell-ebrationframes.htm*
- Concord Consortium: free downloadable simulations: *http://mw.concord.org/modeler*

Diffusion, Osmosis and Active Transport: *www.concord.org/activities/diffusion-osmosis-and-active-transport*

Osmosis:

www.concord.org/~btinker/workbench_web/models/osmosis.swf

http://mw.concord.org/modeler/molecular.html

- Cornell Institute of Biology Teachers: Physiology: Diffusion Across Biological Membranes: *http://cibt.bio.cornell.edu/labs/phys.las*
- DarylScience: Biology Demos: *www.darylscience.com/DemoBio.html*

See demonstrations #7, "Crisp or Limp Salad"; #8, "Exploding Blood Cells"; #11, "How Does Penicillin Work?"; #12, "A Bill Nye Quickie (Vanilla and Balloon)"; see also *Brain-Powered Science*, Activity #20, Extensions.

- *Democracy and Education*: 1916 book by John Dewey: Columbia University's Institute for Learning Technologies' Digital Text Project: *www.ilt.columbia.edu/Publications/dewey.html*
- Disney Educational Productions: *Bill Nye the Science Guy*: *Cells* ($29.99/26 min. DVD): *http://dep.disney.go.com*
- Egg-citing Egg-speriment: *www.haverford.edu/educ/knight-booklet/theegg.htm*
- Exploratorium: *www.exploratorium.edu/cooking/eggs/kitchenlab.html*
- HyperPhysics, Department of Physics and Astronomy, Georgia State University: Fluids: select diffusion, osmosis and membrane transport for concept maps and explanations: *http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html*
- Miami Museum of Science: Constructivism and 5E: *www.miamisci.org/ph/lpintro5e.html*
- Minnesota Science Teacher Education Project: Osmosis and Gummy Bears: *http://serc.carleton.edu/sp/mnstep/activities/26990.html*
- Nanopedia: Soap Bubbles as Nanoscience (with embedded link to cell membranes): *http://nanopedia.case.edu/NWPage.php?page=soap.bubbles*
- National Center for Case Study Teaching in Science: Osmosis Is Serious Business: *http://sciencecases.lib.buffalo.edu/cs/collection/detail.asp?case_id=283&id=283*
- Polymer Science Learning Center: Diffusion and Gummy Bears: *http://pslc.ws/macrog/kidsmac/activity/bear.htm*
- Salmonella Poisoning:

  Centers for Disease Control and Prevention: *www.cdc.gov/salmonella*

  Mayo Clinic: *www.mayoclinic.com/health/salmonella/DS00926/DSECTION=symptoms*

  Medicine.com: Salmonella: *www.medicinenet.com/salmonella/article.htm*

- San Diego State University: Biology Lessons for Prospective and Practicing Teachers:

    Cells: *www.biologylessons.sdsu.edu/ta/classes/lab7/index.html*

    Osmosis: *www.biologylessons.sdsu.edu/ta/classes/lab5/index.html*

- Science Cartoons Plus: The Cartoons of S. Harris (e.g., examples of macroscopic cells): *www.sciencecartoonsplus.com/index.php*

    See also other sites listed in Activity #12.

- Science-Class.net: Osmosis and Diffusion (contains many external links for middle-school level): *http://science-class.net/Biology/Osmosis.htm*
- Science NetLinks AAAS: Plasmolysis in Elodea Plant Cells (lab): *www.sciencenetlinks.com/lessons.cfm?BenchmarkID=5&DocID=106*
- Serendip: Hands-on Activities for Teaching Biology to High School or Middle School Learners: See Diffusion and Investigating Osmosis: *http://serendip.brynmawr.edu/sci_edu/waldron*
- Steve Spangler Science: The Egg in the Bottle Trick and How to Make a Folding Egg:

    www.stevespanglerscience.com/content/experiment/00000022

    www.stevespanglerscience.com/content/experiment/how-to-make-a-folding-egg

- Teachers' Domain: Cell Membrane: Just Passing Through (lesson and simulation): *www.teachersdomain.org/resource/tdc02.sci.life.cell.membraneweb*
- Wikipedia: Osmosis: *http://en.wikipedia.org/wiki/Osmosis* (includes a visual model)
- Wolfram Demonstrations Project: Surface area increase by size reduction (animated): *http://demonstrations.wolfram.com/SurfaceAreaIncreaseBySizeReduction*

Answers to Questions in Procedure, steps #2–#5

2. *Engage:*
   a. Yes, all living things are made up of cells, with the possible exception of viruses, which are considered a somewhat unique category. Most cells are, in fact, microscopic. But an unfertilized egg is a single cell, although it lacks one-half of the required genetic material, so it cannot grow and develop into a living bird. Fertilized egg cells of any species are among the largest single cells, with most of the space occupied by food reserves for the initially microscopic but growing embryo. Human egg cells produced by females are quite large for human cells, about the size of a period—huge compared to male sperm cells.
   b. The cell membrane maintains an internal environment that is different from its external environment or "home neighborhood" by controlling inputs and outputs. Cell membranes operationally define "self" as distinct from "environment" at the molecular level. But the self is an ever-changing dynamic system undergoing constant repair and/or programmed death as determined by the cell's DNA.
   c. Yes, every egg has a cell membrane that is distinct from the shell. If desired, students can examine the membrane that remains attached to the shell of a cracked fresh and/or hard-boiled egg. Most students will not have previously noticed it or considered that eggs, like all cells (including those that have cell walls), have a cell membrane.
   d. Any acid will react with and dissolve the calcium carbonate shell.
3. *Explore:*
   a. Because the membrane appears flexible (like a balloon) and all membranes have molecular-level holes, it is likely that small molecules could pass through the membrane. An embryo would need to import oxygen and export carbon dioxide and water during cellular respiration that must occur 24/7 in every cell.

b. Water is the largest component of eggs, like all cells. Changes in water content could be noted by measuring the mass and/or circumference of the egg and the volume of liquid left in the container before and after the soaking. In the case of the de-shelled egg soaking in water, the water level in the container drops as the egg enlarges. Conversely, the corn syrup solution increases in volume slightly and becomes somewhat diluted. Typical initial egg circumferences may be 15–17 cm in the longer and 13–14 cm in the shorter dimensions. Subsequent changes in the 1–2 cm ranges are typical.

4. *Explain:*

   a. The meshing sorts "molecules" by size, allowing only the smaller ones to pass.
   b. The smaller objects that pass through the grid or "cell membrane" represent water, and the larger ones that cannot pass through represent larger biomolecules in the cell.
   c. In the model, gravity causes the particles to "fall down" (in one direction only) through the holes versus real cell membranes that are semipermeable in both directions.
   d. Water moves from a region of higher water concentration to one of lower water concentration; this concentration gradient is another type of energy gradient. Given the movement of other chemicals into and out of the cell, water has to be able to move in both directions to maintain homeostasis.

5. *Elaborate:*

   Part 2: The answers lie in the surface-area-to-volume scale effects that restrict movement of materials in and out of cells, which greatly restricts the size of prokaryotic cells. Eukaryotic cells increase their effective surface area by way of their many internal, membrane-bound organelles and rely on more complex active transport mechanisms more than "simpler" bacteria are able to do. Similarly, macroscopic, multicellular, eukaryotic organisms have innumerable ways of gaining surface area to volume and specialized structures and body organizational plans (e.g., villi in the small intestines and aveoli in the lungs). But surface-area-to-volume effects still influence body designs and physiological functions for organisms as small as shrews and as large as elephants and whales. The concept of scale is a big idea regardless of the size of the organism.

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