More

Brain-Powered Science

Teaching and Learning With Discrepant Events

Thomas O'Brien

NSTApress
National Science Teachers Association

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Arlington, VA

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Acknowledgments

As with the first book in this three-volume series, I gratefully acknowledge two categories of teachers who nurtured my curiosity and inspired me to look at nature with a sense of wonder and awe. First of all, to my former science teachers at the primary, secondary, tertiary, and graduate levels who introduced me to the FUNdaMENTALs of science in ways that "walked the talk" of research-informed best practices, I'd like to say thank you. Second, I owe a debt of gratitude to the many scientists and science educator-authors who have developed and/or refined discrepant-event-type science demonstrations. Since my decision in the late 1960s to become a teacher, I've actively analyzed numerous engaging expert science demonstrators and books on the topic (e.g., Michael Faraday's famous Christmas Lectures, Mr. Wizard's books and TV shows, Hubert Alyea's *Tested Demonstrations in Chemistry*, Bassam Shakashiri and the Institute for Chemical Education, Tik Liem's *Invitations to Inquiry,* and many more in between). I'm always amazed by how many variations on a theme are possible and how far back into the history of science our best instructional activities can be traced. With this book series, I do not claim to have created any particular demonstration. Instead, my unique contribution has been one small but creative idea—namely, to use discrepant-event activities as dual-purpose models for inquiry-based, interactive teaching-learning and as visual participatory analogies for science teacher education.

With this second book, I'd also like to acknowledge my first and most important teachers, my father (deceased, but still alive in me) and mother (who continues to be a role model for how to stay young as one grows old). We don't get to pick our parents, but I don't think I could have done better. The 1930s Depression, the accidental death of his father, and the WWII enlistment of an older brother left Dad working a full-time job as a high school junior who never finished school. Later on, to support my siblings and me with his hard-working partner, my mom, Dad often held multiple jobs at one time. Among the many lessons that my parents taught me, those that have most influenced this book series and hold special relevance to the profession of teaching are the following:

1. The best teachers (and most powerful lessons) walk the talk; they do not rely on words alone, but rather model the kinds of behaviors they want their "students" to emulate.

(continued)

2. Depending on how you choose to frame reality, work can be FUNdaMENTAL. If your "payment" for work is primarily money, you will always be underpaid. Doing good, quality work with a smile and a sense of playfulness makes people better and life more enjoyable.
3. You should always strive to do your best (given your skills and abilities at a given point in time) and then feel good about your efforts, regardless of how they rank relative to others; you should strive to beat your own former best.
4. Be serious about your efforts, but not overly serious about yourself; we're fallible—get over it. Be able to laugh and learn from your "miss-takes."
5. Put something back in the pot; to whom much is given, much is expected; and the best way to pay back a gift is to pay it forward.

With personal ownership of this book's shortcomings and grateful acknowledgment to my many "teachers" for their invaluable contributions to its quality, I invite the teacher-readers of this volume to remove the weaknesses and improve the strengths of these activities as you use them to invite your students to "stand on your shoulders" to see and travel farther.

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 co-author 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

As a science teacher-educator, I have the pleasure of addressing several audiences with my second NSTA Press book. For returning grades 5–12 preservice and inservice science teachers who have already read *Brain-Powered Science: Teaching and Learning With Discrepant Events*, welcome back. Because you are already familiar with the idea of dual-purpose activities designed for use as both inquiry-oriented *science discrepant events* and *science education analogies*, you may wish to proceed directly to the first activity, "Comeback Cans." You can also continue with this introduction to get a sense of how this book—though similar in format and approach—differs in scope from the previous book.

I'm also delighted to introduce new teacher-readers to a specially designed science education professional development book. *More Brain-Powered Science* was written so you can profit from it without having already used my previous book (although I encourage you to consider doing so). For both groups of reader-users, this introduction provides an overview and context for what this book has to offer. This book series embraces the professional development recommendations developed by NSTA (2003, 2004a, 2006, 2007a, 2007b) and ASTE (2004) and framed as a challenge in the *National Science Education Standards* (NRC 1996):

> The vision of science and how it is learned will be nearly impossible to convey to students in schools if the teachers themselves have never experienced it … preservice programs and professional development activities for practicing teachers must model good science teaching (p. 56) … Involve teachers in actively investigating phenomena that can be studied scientifically, interpreting results, and making sense of findings consistent with currently accepted scientific understanding (p. 59) … Teachers also must have opportunities to engage in analysis of the individual components of pedagogical content knowledge—science, learning, and pedagogy—and make connections between them. (p. 63)

Effective science teachers catalyze and scaffold student learning by practicing both the science and art of science teaching (O'Brien 1991). Books such as *The Art of Teaching* (Highet 1950) and *The Courage to Teach* (Palmer 2007) feature the artistic, human relations, and intrapersonal aspects of teaching. Though perhaps less introspective, the craft of science education has a long history of exemplary practitioners. Scientist-teachers such as Michael Faraday (1791–1867), Thomas Henry Huxley (1825–1895),

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Richard Feynman (1918–1988), Carl Sagan (1934–1996), and Stephen Jay Gould (1941–2002) earned wide acclaim for their insightful writings, thought-provoking classes, and engaging public presentations that featured *inquiry-oriented discrepant-event demonstrations-experiments* and/or *engaging analogies* to raise fundamental questions about science. (The following sources describe a variety of pedagogically useful science analogies: Camp and Clement 1994; Gilbert and Watt Ireton 2003; Hackney and Wandersee 2002; Harrison and Coll 2008; Hoagland and Dodson1998; Lawson 1993.)

Great scientist-teachers of any era intuitively practice science teaching as a performing art (Tauber and Sargent Mester 2007) by integrating the fun and mental aspects of intellectual playfulness. Similarly, educational philosophers from Socrates (470–399 BC) to John Dewey (1859–1952) and educational psychologists such as Lev Vygotsky (1896–1934), Jean Piaget (1896–1980), David Ausubel (1918–2008), and Jerome Bruner (1915–) have advocated for interactive instructional strategies that build on the foundation of students' prior knowledge. More recently, cognitive science research has further developed the science of science teaching as an activity that should be inquiry-based from both students' and teachers-as-learners' perspectives (APA 1997; Bransford, Brown, and Cocking 1999; Bybee 2002; Cocking, Mestre, and Brown 2000; Donovan and Bransford 2005; Mintzes, Wandersee, and Novak 1998; NRC 2000, 2007, 2010; NSTA 2004b).

This book series reflects the dual scientific and artistic nature of science teaching and is based on the following premises that bridge the gap between educational theory and practice:

1. Although cognitive learning theory and the neurobiology of emotion, perception, and cognition are in the infancy stages of development, the foundation for a science of *interactive-constructivist* science teaching has been set and is ready for use. Teaching-learning is an *interactive* process with respect to student←→teacher, student←→phenomena, and student←→student encounters. It is a *constructivist* process of learner-centered conceptual construction (rather than transmission, reception, and absorption). Given research on the science and art of science teaching, we no longer need to simply wait for great teachers to be born. Whether we are preservice student teachers, novice practitioners, competent experienced veterans, or master teachers, there are best bet steps

we can take to enhance our pedagogical content knowledge (PCK) and skills (Cochran 1997; Hagevik et al. 2010; Shulman 1986, 1987). And as we grow as professionals, we become more effective at helping our students develop as self-directed lifelong learners, our classrooms as collaborative learning communities, and our schools as exciting learning organizations.

2. Learners' often somewhat hidden prior conceptions need to be activated and challenged (Driver, Guesne, and Tiberghein 1985; Driver et al. 1994; Mintzes, Wandersee, and Novak 1998, 2000) so valid precursor ideas can be built on and extended, misconceptions can be clarified (see Appendix A), experiential and conceptual holes can be addressed, and learners can be deeply engaged in the fun work and hard play that is learning at its best. Analogically, learning can be viewed as an act of continual collaborative conceptual construction, renovation/remodeling, and expansion, where what the learner already knows (or believes to be so) influences how educational interventions are perceived and reconceived. Experientially based teaching intentionally nurtures metacognitive awareness by encouraging productive conversations between learners' prior conceptions and new experiences. *Discrepant-event activities* are powerful pedagogical tools in that their unexpected, initially anomalous outcomes stimulate the senses, catalyze conversation (both internal and external), and excite exploration that leads to conceptual conflict resolution (see *Brain-Powered Science*, pp. 350–351 for optional readings on related research).

3. Teachers play a central, catalytic role in student learning as mediated by more than their professional passions and idiosyncratic personalities (NCMST 2000; NCTAF 1996, 1997; NRC 2001a; NSB 2006; NSTA 2007a). Teachers design, implement, and revise unit-level teaching cycles and yearlong and multiyear learning progressions that address the following questions: (a) Where do we want our students to travel? [curriculum standards] (b) How can we best help them get there? [instructional strategies and sequences] (c) Where are our students relative to the target destination at any given point in a unit? [assessment system of curriculum-embedded diagnostic, formative, and summative metrics] (d) Based on this continuous cycle of "intelligence gathering," what curricular and instructional adjustments are needed to scaffold and support student learning? Curriculum-Instruction-Assessment (CIA) is an integrated system with both feedback (within a given unit)

and feed-forward loops (that project into subsequent units); they are not separate functions performed in a consecutive linear sequence without input from changing circumstances (Enger and Yager 2001; Liu 2010; Mintzes, Wandersee, and Novak 2000; NRC 2001b, 2001c). Effective CIA focuses on "big ideas" and is somewhat holographic in that each individual learning activity, lesson, and unit contains elements of the whole.

4. "Teachers tend to teach as we were taught" is a positive, promising statement if
   - we "stand on the shoulders of giants," including our own exemplary former teachers and models from the history of science;
   - we become lifelong learners who engage in continual, collaborative professional development by learning with and from our science department colleagues, networking with teachers outside our school, and participating in professional associations such as NSTA that promote research-informed best practices (NSTA 2010a; Tobias and Baffert 2010); and
   - we use our classrooms as action research labs and invite peers to join us in job-embedded professional learning communities and critical friends groups that collaborate on the design, implementation, and evaluation of educational experiments (Coalition of Essential Schools Northwest n.d.; DuFour and Eaker 1998; Mundry and Stiles 2009; NSTA 2010a). Effective teachers, departments, and schools reflect on their actions (Schon 1983; Appendix B in this book). Critical, collaborative analysis of our educational practices enables us to articulate and reform our often unexamined pedagogical theories in action. Rather than regression to the norm that spreads average practice, enculturation of new teachers and revitalization of experienced ones should cause progression to best practices that continuously challenge individual and institutional inertia.

With these premises in mind, both *Brain-Powered Science* and *More Brain-Powered Science* feature science *discrepant-event activities* as instructional activities that can be used for two distinct, but linked, purposes. First, the activities serve as *model inquiry-oriented science lessons* for use in preservice teacher education classes, inservice professional development settings, and the teachers' own grades 5–12 classrooms. Whether done as a hands-on exploration (HOE), interactive demonstration-experiment, or a data-based discussion, a discrepant event's surprising, often counterintuitive, outcome creates cognitive disequilibrium that causes learners to turn over or "HOE the ground" of what they already know (or what they believe to be so). Anomalous outcomes generate a need to know that motivates learners to reconsider their prior conceptions to see which ones need more "water, sunlight, and fertilizer." Equally important, discrepant events also activate and help students assess misconceptions, or "weeds that need to be uprooted," to make room for the seeds of new, more scientifically valid ideas. Purposefully puzzling activities can be used anywhere in a unit, but they are especially effective for diagnostic and formative assessment of learners' evolving mix of science conceptions and misconceptions.

Second, and unique to these two books, these same discrepant event activities serve as *visual participatory analogies for science teacher education and/or model examples*—to catalyze the teacher-as-learner's creative use of research-informed science education principles. Visual participatory analogies are a new professional development strategy in which teachers interactively participate as learners and use discrepant-event science phenomena in ways that metaphorically help them bridge the science education theory–practice gap (O'Brien 2010).

More Brain-Powered Science features some key implications and applications of cognitive learning theory and research as they relate to science education. Specifically, it focuses on interactive teaching and experiential participatory learning; human perceptions as a window to conceptual construction; learning as a psychologically active, minds-on process that depends on activating attention and catalyzing cognitive processing; and the role of prior knowledge, cognitive inertia, and misconceptions. The activities in this book will review some of these learning principles but use them as a lens to probe more deeply into other relevant curriculum-instruction-assessment (CIA) issues that are commonly explored in preservice science methods courses and inservice professional development programs.

Returning readers will note that a smaller range of science concepts (see Appendix C) is covered in this book because this book focuses more on modeling how to develop students' inquiry and process skills in the context of activities on the nature and history of science, mathematics, measurement, and science-technology-society issues and how to use assessments to inform learning and transform teaching. As such, a number of the activities in this book (e.g., #2, #5, #9, #21, and #22), though engaging discrepant events, are not classic, manipulable experiments designed to introduce specific science concepts.

Introduction

Teachers have a limited time to devote to personal learning and professional development relative to the more immediate, pressing task of preparing for what they're doing tomorrow with students. Both of my books are designed to unlock these two doors with one key. That is, teachers can increase both their science content and pedagogical content knowledge and expertise by testing out and reflecting on the impact of these activities in their own grades 5–12 classrooms as a form of job-embedded professional development (see Appendix B for a demonstration-lesson analysis form).

Organizational Structure of the Book

This book's 22 interactive, experiential learning activities (and approximately 80 related Extension activities) are clustered into 5 sections that closely parallel the NSTA Standards for Science Teacher Preparation (NSTA 2003). Professional development specialists and college-level science teacher educators may use the separate sections as a framework for a series of linked professional development sessions or in more formal, credit-bearing science methods courses. Given the range of topics covered, this book (especially when combined with its predecessor) can serve as an activity-oriented supplement to more conventional science teaching methods books (e.g., Bybee, Carlson Powell, and Trowbridge 2008; Chiappetta and Koballa 2010; Gallagher 2007; Lawson 2010). Or, if supplemented by instructor-selected readings, this book can be used in lieu of conventional methods books. Nearly every activity features both the nature of science (Abd-El-Khalick, Bell, and Lederman 1998; Aicken 1991; Bell 2008; Clough 2004; Cromer 1993; Lederman 1992, 1999; McComas 1996, 1998, 2004; NSTA 2000; Wolpert 1992) and the nature of teaching and learning (Michael and Modell 2003; Michaels, Shouse, and Schweingruber 2008; Mintzes, Wandersee, and Novak 1998). Individual grades 5–12 science teachers not affiliated with a course or professional-development program can explore the activities as nonsequential, inquiry-based lessons as linked to their instructional scope and sequence (see Appendix C). In this case, the science education themes will be encountered on a need-to-know basis in the context of regular classroom teaching.

Section 1: Welcome Back to Interactive Teaching and Experiential, Participatory Learning

This foundation-setting section is predicated on the notion that science teaching that leads to student learning is not a simple one-way process of active knowledge transmission (i.e., teaching as telling) and passive reception and absorption (i.e., learning as listening). Instead, the teaching ←→ learning dynamic system is better conceptualized as a psychologically and socially interactive, constructive process that includes both inside→ out and outside→ in exchanges between learners' internal neural networks and their external educational environments (i.e., teacher, peers, and physical and virtual phenomena). Activity #1, "Comeback Cans," uses a classic, hands-on discrepant event to invite teachers to consider how interactive teaching and participatory learning can motivate students to develop an "I can do science" attitude and come (back) to science class with anticipation and leave with regret (rather than the reverse). For teachers new to the idea of visual participatory analogies, the activity also uses a racing metaphor to raise the question of whether going faster is truly a winning strategy for maximizing student learning.

Activity #2, "The Unnatural Nature and Uncommon Sense of Science"—although not designed as a conventional discrepant event or a visual participatory analogy—helps establish the broader context and need for the rest of this book. It uses engaging visual, auditory, and physical props to help learners brainstorm a list of seemingly outrageous yet well-established core science ideas and use that list to discuss why learning science can be unnatural (or at least a somewhat unique challenge as compared to other school subjects).

Section 2: Science as a Unique Way of Knowing: Nature of Science and Scientific Inquiry

Activity #3 opens this section with a series of discrepant-event-based teacher demonstrations and hands-on explorations on the concept of density. Analogically, the argument is made that the failure of students to learn science cannot be viewed solely as a problem of students being "too dense." Instead, the failure to learn must be viewed as a system phenomenon like floating and sinking, where the educational environment must be designed to support student learning. Perhaps we load students down with too many conceptually heavy ideas to fit in the instructional time we allot. This activity and all the activities in *Brain-Powered Science* and *More Brain-Powered Science* were designed to meet the user-friendly S_2EE_2R criteria of being Safe, Simple, Economical, Enjoyable, Effective, and Relevant for both teachers and grades 5–12 students. See Appendix A in *Brain-Powered Science* for the research-based support for these criteria and Appendix B in this volume for a related demonstration-lesson analysis form. Five of the seven activities in this section use no-cost, inquiry-oriented paper-and-pencil puzzles (PPPs) to activate and confront common misconceptions (and conceptual holes) related to the nature of science (NOS).

The American Association for the Advancement of Science (1993), National Research Council (1996), National Science Teachers Association (2000, 2003/Standards #2 and #3), and other professional organizations agree that the NOS and inquiry should be central themes to frame science content in the context of how we know what we know (i.e., epistemology). As a field of study, the NOS is situated at the intersection of the history, philosophy, and sociology of science and cognitive psychology (McComas 1998). Every science lesson inevitably leaves students with some impressions about the NOS. Whether these impressions are scientifically valid and pedagogically motivational or not depends in part on the extent to which the teacher is intentional and explicit in focusing on the NOS as an instructional objective. An advantage of analogy-based PPPs is that they help students develop scientific habits of mind and inquiry skills without requiring prior knowledge of particular science concepts that would burden some learners and give an advantage to others. Also, given the PPPs' focus on scientific reasoning skills, these activities can be used in physical, Earth, and life science classrooms at nearly any point during the school year.

The Science Education Concepts feature of each of the seven activities in Section II also briefly reviews one of the seven principles of activating attention and catalyzing cognitive processing that were a major focus of *Brain-Powered Science*, Section III. Every activity in both books is designed in light of these principles and implicitly focuses on the NOS, but Section II explicitly features these ideas to help draw special attention to them. Effective teachers treat the NOS and learning how to learn science as a stage-setting, introductory topical unit (typically at the start of a course) and as yearlong themes that pervade all subsequent content-based units.

Section 3: Science for All Americans Curriculum Standards

Although the United States does not have an official, nationally mandated science curriculum, we have a default one based on the limited diversity of textbooks that dominate the market at any grade level or science subject area and the increasing importance and relative uniformity of high-stakes, state-mandated exams. Textbooks and tests are slowly moving in the direction called for by the *Benchmarks for Science Literacy* (AAAS 1993), the

National Science Education Standards (NRC 1996), and *A Framework for Science Education, Preliminary Public Draft* (NRC 2010). But how teachers conceive curriculum and operationally translate it into their daily instructional practices is at least as important to school science reform as new and improved textbooks and tests.

Section III includes eight activities that challenge teachers with visual participatory analogies that link curricular decisions to a compass, a horse race, chemistry "magic tricks," mathematical quandaries, historical science puzzles, measurements and molecular "magic," a homemade musical instrument, and a series of nested boxes within boxes. The professional development goal of these activities is to make the familiar look strange so that teachers can view standards-based curriculum with a fresh perspective and an eye to continuous improvement (see NSTA 2003, Standard 6). These same activities can also be used to teach grades 5–12 students science content, process skills, and habits of mind. In particular, four of the eight activities (Activities #13, #14, #15, and #17) help students develop interest and skills in measuring and mathematics that are critical to both science-technology-engineering-mathematics (STEM) careers and everyday life. Activity #14 also uses a classic historical story as an example of cross-curricular connections, and Activity #17 models how a big idea or theme (i.e., scale or powers of ten) has major implications in all fields of science and science-technology-society (STS) issues. Collectively, these activities can also provide a vehicle for teacher discussions related to 21st-century needs such as adaptability, communication skills, the ability to solve non-routine problems, self-management, and systems thinking (Hilton 2010). References are provided for individual teachers, teacher teams, and classes who are interested in studying curriculum reform policies and practices and how they can be tested and improved on in their own classrooms.

Section 4: Science-Technology-Society (STS) and Real-World Science Instruction

Science-technology-society (STS)—including but broader in scope than environmental education—was a major programmatic thrust of NSTA in the 1970s, 1980s, and 1990s, as featured in a series of NSTA position statements (NSTA 2010b), books, and journal articles. STS is also supported by the NSTA *Standards for Science Teacher Preparation* (NSTA 2003, Standards 4 and 7), the *National Science Education Standards* (NRC 1996), the AAAS *Benchmarks* (1993), and more recent calls for science-technology-engineering-mathematics education (NAS 2007; NRC 2010; STEM Education Coalition). Debates continue about the relative efficacy of a social-issue-first, science-content-follows approach versus an approach that infuses STS concepts and real-world examples in the context of a more conventionally arranged "science first" curriculum. A one-size-fits-all approach is rarely as appropriate as having options for different students, grade levels, teachers, science fields, and schools. In the context of the 5E Teaching Cycle, STS issues can be featured during the Engage phase (i.e., to motivate interest and create a need to know) and the Elaboration or Evaluation phases (i.e., to challenge learners to become scientifically literate as they apply and extend their understanding in real-world contexts).

Activities #18–#20 provide examples of how STS can be infused into science instruction to make it more meaningful and relevant to students (see also a number of Extension activities throughout the book). The first two activities involve hands-on, minds-on, analogy-based simulations of phenomena that could not be directly experienced in a safe way (i.e., the spread of infectious diseases and the environmental effects of mining). The third activity plays off the analogical image of a lightbulb as a symbol for creativity to prompt learners to consider how informed personal consumer habits can make a big difference (i.e., think globally, act locally). Though individual and societal changes always involve trade-offs, new technologies often provide win-win options that make both economic "cents" and environmental sense. Teacher resource materials in this section help teachers incorporate more real-world STS concepts and issues into their courses whether or not they use an STS-focused textbook.

Section 5: Assessment to Inform Learning and Transform Teaching

Misconceptions about assessment that result in testing practices that fall short of best assessment practices include the following:

1. The primary purpose of assessment is to grade and rank students (and perhaps even punish laggards) with postinstruction summative tests (rather than to provide diagnostic and formative feedback to improve learning and teaching).
2. Designing fair and effective paper-and-pencil-based assessments is an easy, relatively trivial task given teachers' years of experience with taking tests (versus the difficult challenge of preparing a test where the

distribution by relative content emphasis and cognitive levels [Bloom et al. 1956] is aligned with both the intended curriculum and the actual instruction).

3. Students need to be taught content knowledge directly but not taught how to take tests (versus research that indicates that familiarity with different types of test item formats and test-taking strategies lowers student anxiety and raises their self-efficacy and actual performance).
4. Taking paper-and-pencil tests for grading purposes is, by necessity, a stress-inducing, regurgitation-type activity for students (versus an engaging challenge where students can learn new and exciting real-world applications).
5. Assessment is distinct from and planned after curriculum and instruction (versus aligned with and embedded into them as part of an integrated, intelligent CIA system in which the whole is greater than the sum of the parts).

The two activities in this section contain sample diagnostic assessments that teachers could adapt for use with grades 5–12 students. The primary purpose of these sample paper-and-pencil tests is to encourage teachers to think more deeply about the power of tests that teach students and inform their own curricular and instructional decisions and actions. They challenge teachers to consider how diagnostic, data-driven decisions to differentiate curriculum and instruction can support continuous improvement in both teachers and students. Resource books and websites on alternative assessments in science are also provided to help teachers with this crucial but very challenging aspect of teaching (NSTA 2003, Standard 8).

Appendixes

Appendix A: Alternative, Naive, Preinstructional, Pre-scientific, or Prior Conceptions Matter

Research points to the fact that in learning new science concepts, the most important variable is what the learner already knows and especially what he or she knows that isn't so. Students' alternative conceptions may be tenacious and survive conventional efforts to simply cover over them with new and improved, scientifically correct but often counterintuitive concepts. Appendix A highlights the top 10 sources of preconceptions and shows how to catalyze conceptual change toward more scientifically valid conceptions. See also *Brain-Powered Science,* Activities #20, #24, and #27–#29, and references in this book, such as Driver, Guesne, and Tiberghein 1985; Driver et al. 1994; Duit 2009; Fensham, Gunstone, and White 1994; Harvard-Smithsonian Center for Astrophysics (i.e., MOSART); Keeley, Eberle, and Farrin 2005; Keeley, Eberle, and Tugel 2007; Kind 2004; Meaningful Learning Research Group n.d.; Olenick 2008; Operation Physics; Osborne and Freyberg 1985; Science Hobbyist; Treagust, Duit, and Fraser 1996; and White and Gunstone 1992.

Appendix B: The S_2EE_2R Demonstration Analysis Form

Activities in the *Brain-Powered Science* series meet the criteria of being **S**afe, **S**imple, **E**conomical, **E**njoyable, **E**ffective, and **R**elevant (see also *Brain-Powered Science*, Appendix A). This checklist is designed for individual science teachers, peer coaches, lesson study groups, mentors, and supervisors to collaboratively analyze live or recorded lessons that feature discrepant-event demonstrations and experiments. The checklist provides feedback to increase both the observer's and the observed teacher's instructional effectiveness. As such, it should be used more as a catalyst for collaborative conversations than as summative assessment.

Appendix C: Science Concept and Process Skills

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

Activity Format

Each dual-purpose discrepant event and experiential learning 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 Embedded Questions. In *Brain-Powered Science* (pp. xviii–xxii), I discussed the purpose and rationale for each of these components, and new readers can probably deduce the purposes from the headings or by working through one activity, so only a few comments are necessary here. Given this book's focus on inquiry-based teaching-learning, the brief Expected Outcome statement and the relatively short explanations of the Science Concepts and Science Education Concepts do not need to be read before attempting a given activity. Inquiry questions embedded in the Procedure and Debriefing sections are designed to help teacher-users discover the gist of the underlying ideas by doing the activity and reflecting on the results. Probing questions are especially important when using discrepant-event activities because if preconceptions are left unexamined, such activities can lead to *new* preconceptions (even as they challenge old ones). Though these questions should also prove helpful when using the activities with grades 5–12 students, they are not intended as teacher-proof scripts. 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 (Chin and Osborne 2008). The Answers to Embedded Questions are intentionally placed at the end of each activity to encourage teachers to approach their own professional development as an inquiry-oriented discovery, rather than a simple 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 perspectives of their own students.

Several format features are designed to serve as catalysts and resources for ongoing professional development. The Extensions are brief descriptions of related inquiry activities that are useful for independent follow-up work by teachers as a *means of assessing and extending their own knowledge of the science and science education concepts* and to support the development of units that link a series of related activities (e.g., the 5E Teaching Cycle will be a primary focus of *Even More Brain-Powered Science*). The Internet Connections provide resources for teachers (e.g., professional development links, written descriptions, and QuickTime 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 web, some links will change URLs or be dropped over time. However, most of the sites are hosted by universities, professional organizations, museums, online encyclopedias, and science supply companies that tend to have stable, long-term presences on the web. In addition to their inclusion in the text, an NSTA Press online, hyperlinked resource will allow readers to access these sites electronically and will 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 activities can be modeled quickly in 15–20 minutes when used as visual participatory analogies for science teacher education or as model science inquiry lessons with science knowledgeable teacher-learners. With instructional time so limited in most professional development settings, the activities are designed to be easy to set up, execute, and clean up. Alternatively, when used as science inquiry activities with grades 5–12 students, the activities could take up to a full class period and ideally would be placed in an integrated instructional unit of related concepts and activities.

Closing Comment

This book is based on the assumption that just as our students learn science by experiencing, thinking, writing, discussing, and doing phenomena-based science with peers, we need similar experiences to grow as teachers of science. Unfortunately, as teachers move from preservice to inservice educational settings, we often find ourselves working in insulated, isolated compartments where we neither give nor receive critical friends-type feedback and collegial support. Science progresses when the results of individual and team efforts are broadly shared, critiqued, and refined. Similarly, the science education profession progresses when we identify, confront, and are challenged to correct and learn from our preconceptions and mistakes, as well as when we share and celebrate our successes.

Rather than use this book on their own, teachers can use it more powerfully in collaborative, teachers-helping-teachers, professional development contexts (Banilower et al. 2006; DuFour and Eaker 1998; Garet et al. 2001; Loucks-Horsley et al. 1998; NRC 2001a; NSTA 2006, 2007a, 2007b; O'Brien 1992; Stannard, O'Brien, and Telesca 1994; Tobias and Baffert 2010; Yager 2005). I encourage you to use my books as vehicles to initiate or expand professional conversations and collaborations with your colleagues in your department, school district, local region, and geographically unbounded electronic networks. Although the frontline in the war against ignorance is the individual classroom, the best science teaching is not a solo enterprise, but one in which the collective, networked *we* achieves much more than the individual, isolated *me*. Career-long learning with and from our students and colleagues as we engage them in interactive, participatory, experiential learning is the hallmark of highly qualified teachers who expect and obtain the MOST from themselves (minds-on science teaching) and their students.

Science Education Topics

As with *Brain-Powered Science*, this book has two focuses: science education and science concepts. The table of contents below is organized to feature the science education themes as developed in the five sections. A second table of contents lists the science concepts alphabetically within fields of science (Appendix C). The book does not need to be used in a 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. Comeback Cans: Potentially Energize "You CAN Do" Science Attitudes	TD/HOE p. 3	kinetic and potential energy, friction, models, POE, BBS, NOS, and TOYS (and STS Extensions)
2. The Unnatural Nature and Uncommon Sense of Science: The Top 10 Crazy Ideas and Challenges of Learning Science	PPP (with audiovisual props) p. 17	NOS: unnatural or at least uncommon way of thinking and the "far out" nature of core concepts and theories

Section 2. Science as a Unique Way of Knowing: Nature of Science and Scientific Inquiry

Activity	Activity Type	Science Concepts and Learning Principle Modeled
3. Dual-Density Discrepancies: Ice Is Nice and Sugar is Sweet	TD TD TD HOE TD/HOE STS/BIO HOE p. 33	NOS, POE, and density (all activities), and dissolution and diffusion importance of consistent, reproducible empirical evidence, logical argument, and skeptical review to develop theories that have both explanatory and predictive value ** Novelty & Changing Stimuli **
4. Inferences, Inquiry, and Insight: Meaningful Mistakes	PPP p. 47	BBS, POE, and the inferential and tentative/subject-to-revision NOS ** Puzzles and Discrepant Events **
5. Pseudoscience in the News: Preposterous Propositions and Media Mayhem Matters	PPP/STS p. 57	scientific literacy and the NOS: Science and pseudoscience (astrology) are both creative, but the latter is not balanced by logical argument and skeptical review of empirical evidence. ** Cognitive Connections and Meaningfulness **
6. Scientific Reasoning: Inside, Outside, On, and Beyond the Box	PPP HOE options p. 71	NOS, BBS, and POE indirect evidence, measurement skills, and inferential reasoning to discover patterns ** Multisensory Experiences and Multiple Contexts **

7.	Magic Bus of School Science: "Seeing" What Can't Be Seen	PPP TD option (see Activity 12) *Extensions*: BIO/STS p. 83	BBS and NOS: questions, observations, and inferences are influenced by prior understanding. Internet Connections: NOS instruments (e.g., DAST) * *Emotional Engagement, Connections, and Relevance* *
8.	Reading Between the Lines of the Daily Newspaper: Molecular Magic	HOE p. 93	NOS, POE, biopolymers, explanatory and predictive power of the atomic theory and STS/recycling * *Adequate Time for Learning* *
9.	Pondering Puzzling Patterns and a Parable Poem	PPP p. 107	NOS: pattern recognition, perceptual and conceptual biases, and science as a collective enterprise * *Psychological Rewards* *

Section 3. Science for All Americans Curriculum Standards

Activity		Activity Type	Science Concepts and "Big Ideas"
10.	Follow That Star: *National Science Education Standards* and True North	PAD/HOE p. 119	compass directions, magnets, and NOS + STS Extension
11.	"Horsing Around": Curriculum-Instruction-Assessment Problems	PPP p. 131	problem definition and resolution and visual-spatial intelligence
12.	Magical Signs of Science: "Basic Indicators" for Student Inquiry	TD p. 143	acid-base indicators, solubility of ammonia, evaporation and NOS + Extension: STS Case Study/History
13.	Verifying Vexing Volumes: "Can Be as Easy as Pi" Mathematics	HOE/TD p. 153	volume measurement, metric units, and applied mathematics in science
14.	Archimedes, the Syracuse (Sicily) Scientist: Science Rules Balance and Bathtub Basics	TD/HOE p. 161	history and NOS, volume measurement, water displacement, and density
15.	Measurements and Molecules Matter: Less Is More and Curriculum "Survival of the Fittest"	PAD/HOE p. 173	volume measurement, significant digits, and kinetic molecular theory Extensions: STS case studies on biofuels and EcoFoam
16.	Bottle Band Basics: A Pitch for Sound Science	TD/HOE p. 189	conversion of kinetic energy to sound energy, frequency, and POE + STS Extensions
17.	Metric Measurements, Magnitudes, and Mathematics: Connections Matter in Science	PAD/HOE p. 201	metric system, powers of ten, ppm, ppb + Extensions: Biological diversity and scale effects, atomic theory, geological time, and STS/environmental issues

(continued)

(continued)

Section 4. Science-Technology-Society (STS) and Real-World Science Instruction

Activity	Activity Type	Science Concepts
18. Medical Metaphor Mixer: Modeling Infectious Diseases	HOE/MIX/STS/BIO p. 223	spread of infectious diseases by body fluids (e.g., AIDS simulation)
19. Cookie Mining: A Food-for-Thought Simulation	HOE/STS p. 237	resource conservation and waste management in mining (simulation)
20. Making Sense by Spending Dollars: An Enlightening STS Exploration of CFLs, or How Many Lightbulbs Does It Take to Change the World?	PPP/HOE/STS PAD *optional* p. 247	electrical energy conservation, compact fluorescent versus incandescent lighting, CO_2 and the greenhouse effect, and applied mathematics in science

Section 5. Assessment to Inform Learning and Transform Teaching

Activity	Activity Type	Science Concepts
21. A Terrible Test That Teaches: Curriculum-Embedded Assessment	PPP p. 263	data analysis, pattern recognition, inference making, and assessment
22. Diagnostic Assessment: Discrepant Event or Essential Educational Experiment? #1 Dueling Theories: Flat Versus Spherical Earth #2 Rooting for Plants	PPP p. 279	measurement of pre-experimental conditions and real-world examples and misconceptions related to: Evidence for a Spherical Earth History and Nature of Science Plants/BIO

Classroom 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 use only 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, prior 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 hazardous liquids or gases. When working with solids, such as soil, metersticks, and glassware, 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 and peanut butter allergies and asthma) when using activities that could cause a serious negative reaction.
6. Wash hands with soap and water after doing activities that involve 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 (CSSS 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.

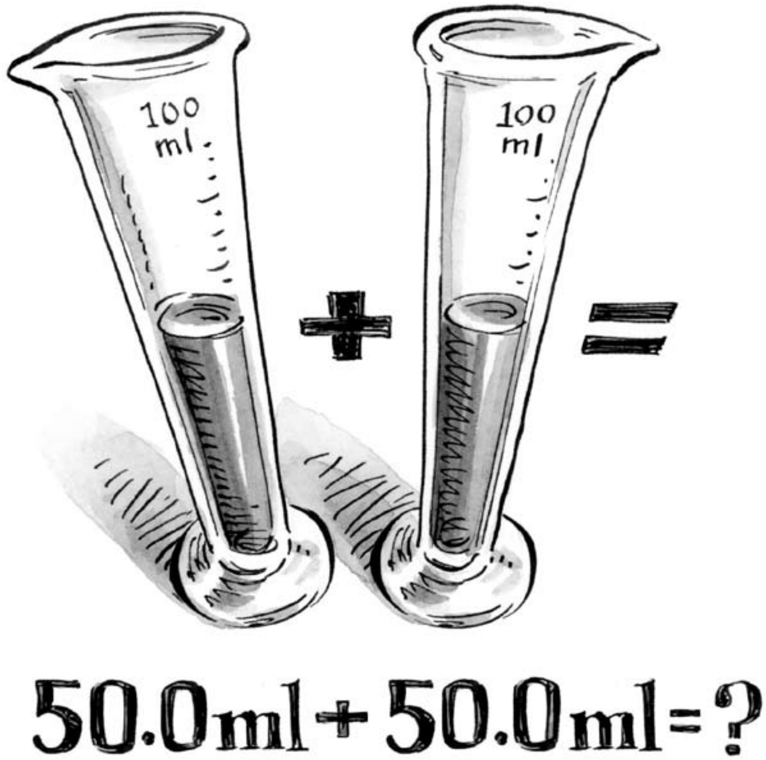
Texley, J., T. Kwan, and J. Summers. 2004. *Exploring safely: A guide for high school teachers.* Arlington, VA: NSTA Press.

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

Activity 15

Measurements and Molecules Matter

Less Is More and Curriculum "Survival of the Fittest"



Expected Outcome

The volume nonadditivity that occurs when combining equal volumes of alcohol and water (e.g., 50.0 ml + 50.0 ml = 96.0–97.0 ml of the mixture) leads to a consideration of the importance of experimenter skill, integrity, and honesty; the "significance" of significant digits; and the atomic/kinetic molecular theory of matter.

Science Concepts

Measurement precision, significant digits (or figures), and the atomic/kinetic molecular theory are all explored. A volume reduction occurs when mixing the two different liquids because of the different sizes and shapes of the ethanol versus water molecules; their intra- and intermolecular forces; and their corresponding, ever-shifting intermolecular "holes." Mass is conserved because atoms are not created or destroyed, but volume is not conserved because the empty spaces between molecules can be reduced via mixing.

Science Education Concepts

An experiment where "more becomes less" is used as *a visual participatory analogy* for the converse idea that less is more with respect to curriculum that has a more focused coverage. The *Benchmarks for Science Literacy* (AAAS 1993), the *National Science Education Standards* (NRC 1996), and *A Framework for Science Education, Preliminary Public Draft* (NRC 2010) argue for uncovering relevant preconceptions and discovering in depth a smaller number of common themes, unifying concepts, or core and cross-cutting big ideas. This research-informed recommendation is in contrast to teaching that attempts to cover a large number of less important concepts, which results in superficial learning that cannot later be recovered from memory and creatively applied by learners (who "miss the forest for the trees"). Also, laboratory inquiry skills are best learned in a meaningful context (i.e., where measurements matter) rather than as decontextualized skills to be used later in a course. Meaningful, exploration-type laboratory investigations that are both hands-on and minds-on are powerful forms of curriculum-embedded, formative assessments. They also create a need to know that can be resolved in subsequent Explain-phase learning activities.

Materials

Teacher Demonstration

- As a student-assisted, interactive teacher demonstration-experiment, this discrepant-event activity requires a minimum of 100 ml of standard laboratory-grade ethanol (or methanol).

Drugstore rubbing alcohol (either ethanol or isopropanol) will only work if the concentration is in approximately the same range. The 50–70% rubbing alcohol varieties will not result in as noticeable a volume reduction because they are already diluted with water.

- About 50 ml of BBs and an equivalent volume of marbles are needed as simple, pourable models of water and ethanol molecules.
- Space-filling molecular models of an ethanol molecule and a water molecule can be purchased from science supply companies or can be made using proportionally sized Styrofoam balls from a craft store (1 in. diameter for hydrogen atoms, 2 in. for oxygen atoms, and 2.5 in. for carbon atoms).
- Several 100 ml and 10 ml graduated cylinders are also needed.

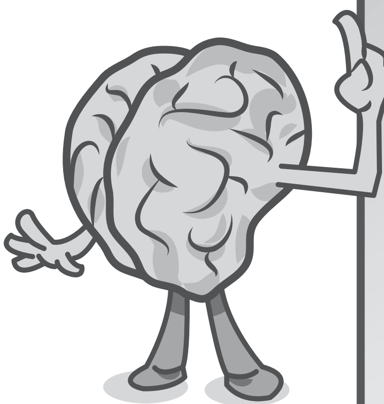
Safety Note

Denatured ethanol [95%] is poisonous to drink but safe to handle if it is kept away from flames or sparks that could ignite it. If this activity is done as a hands-on experiment, students should wear safety goggles, and adequate room ventilation is important.

Hands-On Exploration Option

Depending on the age and maturity of the students and lab facilities and safety equipment (i.e., safety goggles), the teacher may want to do this activity as a modified hands-on exploration. Different teams could be assigned to complete one of the following volume-measurement tasks: adding water to water, adding ethanol to ethanol, or adding ethanol to water. This approach will keep the amount of ethanol-water mixture that needs to be disposed of to a minimum, and it will automatically produce discrepant results across the different teams. Each pair of students will need approximately 50 ml of each of the two liquids they are assigned and two 100 ml graduated cylinders.

Optional: 10-Minute University: The World's Fastest-Talking Man Teaches the World's Greatest Lessons. (2004). An illustrated book and CD by Jim Becker, Andy Mayer, Bob Tzudiker, Noni White, and Mark Brewer (illustrator), with John "Mighty Mouth" Moschitta (CD "lecturer"). New York: Barnes & Noble Books.



Points to Ponder

It is the weight not the number of experiments that is to be regarded.

—Isaac Newton, English physicist and mathematician (1642–1727)

The experiment serves two purposes, often independent one from the other: it allows the observation of new facts, hitherto either unsuspected, or not yet well defined; and it determines whether a working hypothesis fits the world of observable facts.

—Rene J. DuBos, French American bacteriologist (1901–1982)

If in some cataclysm, all scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis (or atomic fact, or whatever else you wish to call it) that all things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another. In that one sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied.

—Richard Feynman in *Six Easy Pieces: Essential Physics by Its Most Brilliant Teacher* (1996)

Thus every discipline is like a hologram … Holographic logic was anticipated two and a half centuries ago by William Blake in a simple image from "Auguries of Innocence," where he suggests that we can "see a World in a Grain of Sand." Every academic discipline has such "grains of sand" through which its world can be seen. So why do we keep dumping truckloads of sand on our students, blinding them to the whole, instead of lifting up a grain so they can learn to see for themselves? Why do we keep trying to cover the field when we can honor the stuff of the discipline more profoundly be teaching less of it a deeper level?

—Parker J. Palmer in *The Courage to Teach* (1998, p. 125)

Procedure

1. For both teachers and students, mention that the keys to understanding science are learning the core concepts, how they interrelate, and how they apply to real-world contexts, as well as learning how to think scientifically (including how we know what we know in science). Share the quotes from Newton and DuBos as an introduction to laboratory-based learning.
2. The following steps are written for an interactive teacher demonstration experiment with volunteer assistants to help make the measurements and mixtures.
    a. Use two 100 ml graduated cylinders to separately measure out as close to 50 ml of liquid #1 (ethanol) and 50 ml of liquid #2 (water) as possible. Volumes in the range of 49.6–50.0 ml are fine, but it is important to not exceed 50.0 ml in either graduated cylinder. The identity of the two liquids can be shared or left as unknown. If desired, an optional drop of food coloring added to one or both of the liquids provides an easy visual indicator of when the two liquids are thoroughly mixed in the next step (e.g., red + blue = purple or yellow + blue = green; see also Extension #2 (p. 182) for a related variation on density). Alternatively, the result may be even more discrepant if both clear, colorless liquids appear to be the same (although the difference in smell between the two liquids may be noticed by the assistants). In either case, ask the assistants to take their unmixed liquids to several classmates to verify the precise volumes of the unmixed liquids. Or, if a document camera is available, focus on the meniscus so everyone in the class can simultaneously see the volumes. Ask: Does it matter if we record the results as 50, 50.0, or 50.00 ml, or are these numeric values all the same? What does the term *precision* mean, and how does it relate to the particular measuring device used? Be sure to point out that the meniscus curves downward in both liquids, and volumes should be read with the bottom of the curve at eye level. If the volumes suggested by the learners are less precise, ask them to recheck their figures. If the volume of either of the two liquids exceeds 50.0 ml, ask students to tilt the graduated cylinders sideways and

use a long plastic eyedropper to remove and discard a little of the liquid from one or both of their graduated cylinders before mixing them together in the next step.

b. Carefully pour (without spilling or splashing) liquid #1 into the graduated cylinder of liquid #2 and back again into graduated cylinder #1 so that the two are combined and thoroughly mixed in one graduated cylinder. Ask the learners to note any observations that accompany the mixing and think how these might help account for the final volume of the mixture.

c. To help learners better visualize the approximately 3–4 ml reduction in volume, place the same volume of water that was lost into several 10 ml graduated cylinders to pass around the room. Brainstorm possible explanations for this volume reduction. Does the reduction in volume imply that matter was also lost? Why or why not? How could this be checked or controlled for in the experimental design?

d. As time permits, collectively discuss how to check and control for various possible experimental factors. For example, repeat the experiment by adding together two graduated cylinders of 50.0 ml of liquid #1 and then two cylinders of liquid #2. In both cases, the combined volumes obtained when mixing the pure liquids with themselves should be within 0.5 ml of the algebraic sum (100 ml). Invite other possible explanations to account for how more has become less when adding two different liquids but not when adding pure liquids together. Whether or not the idea of different-size intermolecular holes is mentioned, move on to the next step.

e. Perform a silent demonstration of adding 50 ml of BBs to 50 ml of marbles, with a slight shaking to cause mixing. Elicit ideas as to how this simple macroscopic model might relate to the nonadditivity of liquid mixtures versus the volume additivity of pure liquids. See if anyone thinks he or she knows the identity of the two originally clear, colorless liquids. Identify the liquids as ethanol and water. Challenge the learners to discuss the strengths and weaknesses of the BB-and-marble model and the space-filling molecular model. Hold up larger, more realistic-looking space-filling (not ball-and-stick) models of each molecule to show their relative size and shape (or distribute kits so each group can construct their own models of H_2O and CH_3CH_2OH). Molecular animations can also be used to show students a more dynamic molecular scale perspective (see Internet Connections: Cell Biology Animations).

f. Optional Challenge Question: How might we explain a situation where two different liquids were physically mixed together (without a chemical reaction) and the volume of the mixture was observed to be greater than their additive sum?

Debriefing

When Working With Teachers

Ask how many of them had previously done experiments (as students) that showed that significant figures are truly significant in science or who were provided a compelling yet simple example of the need for a particulate (or molecular) theory of matter. Discuss how in attempting to cover more and more content (and perhaps even complete a set number of lab exercises), we are less likely to teach in inquiry-oriented ways that uncover the nature of science (i.e., its foundation on empirical evidence, logical argument, and skeptical review); promote an ability to creatively transfer lessons learned to new contexts; or help students construct meaningful learning that lasts (and can be recovered from memory and used) long beyond a test. Students are typically asked to accept truly far-out, outrageous ideas such as atoms and molecules on faith on the authority of the teacher or textbook (e.g., see Activity #2). Consider, for instance, that when you hold 18 ml (or 18 g or 1 mole) of water in your hand, scientists believe you are actually holding 6×10^{23} incredibly tiny, V- or Mickey Mouse–shape H_2O molecules. Each molecule is in a state of constant translational, rotational, and vibrational motion (including the internal movements of their three constituent atoms)!

If available, use one of the one-minute audio mini-course summary lectures from *10-Minute University* (see p. 175) as a humorous way to point to the challenge of covering an ever-increasing number of science concepts in one year. Alternatively (or as a complementary prop), hold up a copy of a large science textbook and ask if it is possible to cover all of the book's information in one year. As an option, consider projecting all the end-of-chapter terms—such as from a biology chapter on fungi—to point out that not even all science (or even biology) teachers know (or need to know) all these specialized terms.

Share the quote from *The Courage to Teach* (p. 176) as a lead-in for having the teachers work in groups of four to develop quick preliminary lists of curriculum exclusion principles. These principles or criteria could be used to either eliminate or restrict the time devoted to concepts that are identified as being less important or relevant so that more time is available to spend on big ideas. Compare the teachers' lists of criteria to the following list and to their experiences with Activity #15.

A concept should be *excluded* from (or given restricted time in) a curriculum if it meets the following criteria:

- The only or primary justification for inclusion is that it will be needed for the next course. (*conceptual relevance*)
- It cannot be made understandable (*cognitive accessibility*), given
  - students' cognitive abilities (*developmental appropriateness*)
  - available lab, demonstration, and multimedia facilities and equipment (*demonstrability*)
- A relevant connection cannot be made between the concept and the personal or social environments of the students' lives. (*life applicability, utility, and relevance*)
- It will not play a role in subsequent discussions. (*disciplinary centrality*)
- Its inclusion consistently has been found to confuse and frustrate students and/or dampen enthusiasm for the discipline. (*meaningfulness and motivational appeal*)
- Other more central, FUNdaMENTAL concepts better meet the inclusion criteria implied above, and curriculum time is a factor. ("*survival of the fittest*")

Some teachers might feel this set of criteria would submit traditional curriculum and textbooks to a slash-and-burn-type campaign. Actually, it is more of a call for teachers and curriculum designers to discover the relevance and power of core disciplinary ideas as called for by the *National Science Education Standards* (NRC 1996, p. 109), the *Benchmarks for Science Literacy* (AAAS 1993), and the *Framework for Science Education, Preliminary Public Draft* (NRC 2010, pp. 1–14). In any case, deciding what concepts *not* to teach (or spend only limited amounts of time on) is an important corollary to deciding what to teach, and these decisions need to be informed by local- and state-level standards and assessments rather than driven by what topics happen to be in the textbook.

When Working With Students

Activity #18 can be used to emphasize the importance of faithfully reporting actual results, rather than what you think should happen (or other lab groups' reports). Many famous scientific discoveries have been made when an experimenter noticed something unusual or a mistake and followed up on the serendipitous discrepancy rather than ignoring it as others had done. This activity also serves as an engaging introduction to significant digits and the need for careful measurements as a means of making interesting discoveries. This approach stands in contrast to skills-only labs where students practice for future, potentially more interesting uses. Finally, the activity is one of many (see the Extensions below and Activity #8 in this book, as well as Activity #20 in *Brain-Powered Science*) that can be used to convince students that the atomic and kinetic molecular theory really is a sensible (i.e., its effects can be experienced through the senses and are logical) and powerful explanatory and predictive model for a wide variety of macroscopic events. From a molecular viewpoint, all matter is "holey"—that is, nothing is truly solid.

Extensions

1. *Molecular Mixed Drinks and Density Demonstration*: The previous experiment can be combined with an experiment on density and (im)miscibility by setting up two contrasting large test tubes or graduated cylinders. Fill the first tube approximately halfway with water colored with yellow food coloring; then carefully run approximately the same volume of blue ethanol down the side of the tube to layer it gently on top of the yellow water. This setup up will be relatively stable, as the denser water is on the bottom. Contrast this to the second tube, where you reverse the

order of the liquids by putting the less-dense blue alcohol in first, then attempt to layer the more-dense yellow water on top. In the latter case, mixing of the liquids (and colors, to form green) will occur right away, with the accompanying evolution of heat and gas bubbles as hydrogen bonding and the differential sizes of the two types of molecules cause a reduction in volume. Even in the first setup, random molecular motion will eventually cause the two liquids to mix. If desired, students can see if the time this takes varies with the temperature of the fluids.

2. *Ethanol-Water Mixtures, Magic Money and Mileage: An STS Case Study*: The discrepant event in which a dollar bill soaked in a 50% water and 50% ethanol mixture will ignite and burn without harm (due to the high heat of vaporization of water relative to the bill's kindling temperature; see Internet Connections: About.com) can be used as an attention-grabbing introduction to ethanol-based biofuels. Ethanol-water and ethanol-gasoline mixtures (or gasohol) are currently being used as substitute automotive fuels in countries such as Brazil and the United States (see Internet Connections: Wikipedia). Students can research the STS tradeoffs involved in mixing ethanol with gasoline and devoting agricultural land and potential food products such as corn to the production of renewable biofuels to feed our internal combustion engines.
3. "*Waste Away" With Ecofoam Experiment, Demonstration, and STS Mini Case Study*: Petroleum-based, non-biodegradable, nonrenewable, water-insoluble Styrofoam (polystyrene) packing peanuts can be compared to starch-based, biodegradable, water-soluble ecofoam. Ecofoam packing peanuts will dissolve in a container of water without appreciably adding to the volume of the original water. This allows for a variety of "now you see it, now you don't" science magic tricks and art or construction projects that use water to glue together pieces of ecofoam. Ecofoam can also be detected with an iodine-based starch indicator. Students can explore and debate the tradeoffs by weighing the sources, relative benefits, and environmental burdens of these two alternative types of packing material (e.g., consider if boxes get wet during shipping, if they are stored in a location that could attract rats, or if large quantities of starch were added to natural waterways).

They can also consider the importance of the eco-mantra "reduce, reuse, and recycle." See Internet Connections: Kansas City Public Television's e-Eats program.

Optional Teacher Demonstration: If a fume hood is available, a teacher (wearing safety goggles) can show how Styrofoam's 3D structure breaks down when it melts or dissolves in acetone (i.e., neither term is technically correct, as the acetone simply breaks some of the bonds that enable the polymer to maintain its shape). The small quantity of solid residue remaining (i.e., Styrofoam is mainly air) can be dried and thrown in the garbage, and the acetone can be reused many times. A video of this demonstration can be found in the Internet Connections: Steve Spangler Science.

4. *Repudiating the "Law" of Conservation of Volume*: Other dramatic examples of volume reduction include cases where large quantities of very water-soluble solids (e.g., table sugar or salt) can be added to water with little, if any, measurable increase in the volume of the solution relative to the starting volume of pure water. (*Note:* Total mass is conserved during the dissolution process.) Again, the respective intermolecular "holes" in water and the non-ionic solids and the interionic "holes" in salts allow for an increase in packing efficiency (i.e., this is in addition to the macroscopic spaces between the crystals of sugar or salt in the solid samples). The density of the solution formed is also greater than that of pure water.
5. *Laboratory Learning and Lesson Study*: Use the Internet Connections websites on lesson study and action research, as well as *America's Lab Report* (Singer, Hilton, and Schweingruber 2006), as starting points for a yearlong (or multiyear) lesson study or action research group focused on increasing the effectiveness of laboratory activities used in your school. See also Clark, Clough, and Berg (2000); Clough (2002); Clough and Clark (1994a, 1994b); Colburn (2004); Doran et al. (2002); Hofstein and Lunetta (2003); Lunetta, Hofstein, and Clough (2007); NSTA (2007c); and Volkman and Abell (2003) to further explore ways to redesign lab exercises to become inquiry-based explorations.

Internet Connections

- 3-D Molecular Designs (water model): *www.3dmoleculardesigns.com/news2.php#water*
- About.com: Chemistry: Burning Money Demonstration (uses a alcohol-water mixture): *http://chemistry.about.com/od/demonstrationsexperiments/ss/burnmoney.htm*
- Alcohol + Water: A more complicated perspective on the nonadditivity of volume: *www.als.lbl.gov/als/science/sci_archive/70methanolmix.html*
- *America's Lab Report: Investigations in High School Science*: *www.nap.edu/books/0309096715/html/R1.html*
- Cell Biology Animations (see: water): *www.johnkyrk.com*
- Center for Collaborative Action Research: *http://cadres.pepperdine.edu/ccar*
- Disney Educational Productions: *Bill Nye the Science Guy*: *Atoms* and *Measurement* ($29.99/26 min. DVD): *http://dep.disney.go.com*
- Doing Chemistry: Movies of chemical demonstrations: Mixing alcohol and water in a long tube: *http://chemmovies.unl.edu/chemistry/dochem/DoChem070.html*
- Kansas City Public Television's e-Eats program: Ecofoam versus Styrofoam (PDF download): *www.kcpt.org/eats*
- National Academy of Sciences: National Research Council:

    Board on Science Education (*Framework for Science Education*) *http://www7.nationalacademies.org/bose/Standards_Framework_Homepage.html*

    National Science Education Standards (1996): *www.nap.edu/readingroom/books/nses/overview.html*
- Official M.C. Escher website: *www.mcescher.com*. The work titled *Relativity* makes a great prop when discussing the need for clear, consistent curriculum goals and instruction and assessment (CIA) that align with those goals. Both *Reptiles* and *Drawing Hands* can be used to represent the need for integrative, iterative cycles of CIA. *Bonds of Union* can represent teacher-student interactions.

- Steve Spangler Science: Vanishing Styrofoam (description of experiment + video): *www.stevespanglerscience.com/experiment/00000046*
- Wikipedia: *http://en.wikipedia.org/wiki*. Search topics: action research, ehanol, ethanol fuel, and lesson study

Answers to Questions in Procedure, step #1

1. a. Yes, it matters how many decimal places are included because the different numbers indicate measuring equipment with different degrees of precision. Standard 100 ml graduated cylinders have 1 ml graduation marks, and volumes should be estimated to the nearest 0.1 ml.

   b. After mixing the two different liquids together, tiny gas bubbles are released or created (which might cause a minor volume reduction as they leave the liquid) and some heat is generated (which might cause a short-term volume expansion). Results for the combined volumes should near 96.0–97.0 ml. This is in contrast to the conservation of volume that occurs when a given liquid is added to itself (e.g., water + water or ethanol + ethanol).

   c. Excluding human errors such as misreading the volumes and spilling or splashing the liquids, a variety of factors might potentially contribute to a reduction in the final volume of the mixed liquids: some kind of chemical reaction that produced a new low-solubility gas that escapes and/or a physical change that generated heat that caused a previously dissolved gas to be expelled (in either case, there should be a corresponding reduction in mass that could be measured but is not found); rapid evaporation of one or both of the liquids (short of rapid boiling, this cannot account for the magnitude of volume reduction, and neither of the nonmixed liquids evaporate at a measurable rate in the time frame of the experiment); residual fluid left in the one "empty" graduated cylinder (the mass of this small volume can be checked with an accurate balance), and so on. None of these factors, individually or collectively, can account for this order of magnitude in reduction of volume, and in fact heat alone would cause a slight, short-term expansion of the volume of the mixture. Something else must be going on. Someone may suggest that the two unknown liquids may have different densities (in fact, water has a density of 1.0 g/ml and ethanol 0.79 g/ml) and perhaps the denser liquid "squishes" the other less dense liquid into a smaller volume. This idea gets at a molecular view and the idea of different-size intermolecular "holes" or empty spaces. The next steps in the procedure will explore this hypothesis.

d. No question is asked in this step.
e. The marble-and-BB model clearly shows the idea that the two types of molecules have different sizes and different-size intermolecular holes that allow for some gains in packing efficiency when they are added together. If either marbles or BBs were added to themselves, the final volume would be additive (i.e., volume is conserved), as is true when any liquid is added to itself. Note that whether one adds the same kind of particles together or creates a mixture containing two different kinds of particles, the marble-and-BB model demonstrates the conservation of matter as consistent with doing the experiment with the actual liquids.

   Major limitations of the marble-and-BB model include the following:

   1. The "holes" are filled with air in the macroscopic model unlike truly "empty holes" that exist at the molecular level.
   2. The model's static nature does not reflect the ever-changing location of the "holes" as related to the constant, dynamic motion (or kinetic energy) of the actual molecules in a liquid phase,
   3. The model suggests that water and alcohol molecules are simply different size monatomic elements (such as helium versus neon) rather than more complex molecular chemical compounds.
   4. The model does not reflect the existence or relative strength of intermolecular forces between like and unlike molecules.

In the case of alcohol (marbles) and water (BBs), hydrogen bonding between the two different types of molecules (adhesion) is greater than the cohesive attraction (water-water and alcohol-alcohol), and these forces help contribute to the observed volume reduction. The more detailed space-filling molecular model kit shows the relative size, number, and arrangement of the constituent atoms in alcohol and water molecules, but the model kit also fails to represent either the hydrogen bonding or the dynamic molecular motions. (And, of course, atoms are not colored!) Neither of these two physical models demonstrates the generation of heat and the associated slight loss of dissolved gases (primarily nitrogen and oxygen driven out of solution by the heat) that are observed in the actual setup. Physical models, like analogies, always differ from the real systems they represent, but they provide both explanatory and predictive power to advance the scientific enterprise.

f. If the two different types of molecules repelled each other with enough force, then the final volume could be greater than the simple addition of their individual volumes, as the molecular "holes" would be larger. One example of this phenomenon is the addition of carbon disulfide to ethyl acetate. Chemical reactions between two different liquids that produced new chemical compounds could also conceivably lead to an increase in volume.

Safety Note

This teacher demonstration should not be done unless a fume hood is available and other safety precautions are followed.

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