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Brain-Powered Science

Teaching and Learning With Discrepant Events

Thomas O'Brien

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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 (in this case, a two-balloon balancing act). 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

I owe an immeasurable debt of gratitude to the great science teachers whom I have had the pleasure to learn from and to work with over the years.

My initial inspiration to become a science teacher came from Dan Miller, my high school chemistry and physics teacher and student-teaching mentor. Dan's frequent use of demonstrations and his emphasis on the historical evolution of theories made science both fun and mentally engaging. His gift of the book *Tested Demonstrations in Chemistry*, edited by Hubert Alyea and Fred Dutton and now out of print, catalyzed my interest in exploring the science behind the "magic" of science demonstrations.

When I was an undergraduate student at Thomas More College, the chemistry faculty supported my development of "edu-taining" Chemistry Is Magical programs for elementary classrooms. At the beginning of my work as a secondary science teacher, I was encouraged by Mickey Sarquis and the Cincinnati section of the American Chemical Society (ACS) to develop the skills and confidence to "teach teachers" via the Expert Demonstrator Training Affiliate program.

Later, my mentor at the University of Maryland-College Park, Dr. Henry Heikkinen, guided my dissertation study of a NSF-funded Institute for Chemical Education summer professional development program on chemical demonstrations. Henry's expertise as a writer, editor, and science teacher educator also facilitated my transition to becoming a full-time science teacher educator through early development work on the ACS's Chemistry in the Community textbook. Twenty years later, his insightful critique and encouragement helped me to frame the dual focus of this book: discrepant-event science activities and their use as analogies for science teacher education.

As a professor at Binghamton University, I've benefited from co-teaching grant-funded summer institutes with wonderful colleagues in all four of our science departments. Physicists Andy Telesca (who also reviewed early versions of this book) and Dr. Carl Stannard were especially supportive at the early stage of my development of the dual focus pedagogical strategy. Informal feedback from hundreds of preservice and inservice science teachers has enabled me to refine this approach. I especially appreciate the meticulous review of the science explanations in this book by my former doctoral student, Dr. Douglas Green.

(continued)

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Acknowledgments

I would also like to acknowledge the many scientists and science teacher educators whose independent development of discrepant-event demonstrations and analogies is the foundation of my synthesis of these two teaching strategies. Nearly every science activity in this book has a history that goes back to books published at least 60 years ago; a few activities even go back as far as the late 1800s. Isaac Newton's acknowledgment that he "stood on the shoulders of Giants" is especially relevant with my book.

Finally, I would like to thank my wife and children for their encouragement and support. Everyone's children deserve the very best education that we can provide as we continually strive to grow as both teachers and learners.

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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 last 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 MA and a PhD 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* (*ChemCom*) (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 20 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 of what he has learned with and from the large number of K–12 teachers he has had the privilege to serve.

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Introduction

As current (or future) grades 5–12 science teachers, professional development specialists, or college-level science teacher educators, you have both the privilege and responsibility of asking your students and colleagues to join you as active, lifelong learners. This book invites you to engage in science that involves both hands-on play and minds-on mental processing. The 33 activities will lead you to critically examine and translate into practice your ever-evolving understanding of science and both the science and the art of science teaching. The "dual-purpose" activities—so called because they address science content and science education—are made up of two components:

1. *Discrepant-event science activities for use both in grades 5–12 classrooms and as models of inquiry-oriented science lessons for use in preservice classes and inservice professional development settings.*

   Whether done as a hands-on activity or demonstration, the discrepant event's surprising, often counterintuitive outcome creates cognitive disequilibrium that temporarily throws learners mentally off-balance. For example nearly everyone "knows" that a sharp needle will pop a balloon, but in Activity #20 learners observe a long, sharp needle skewer a balloon without bursting the balloon. The unexpected outcome of such a discrepant event generates a need-to-know that motivates learners to thoughtfully reconsider their prior conceptions.

   Discrepant-event activities can be used anywhere in a unit. They are especially effective for diagnostic and formative assessment of learners' evolving mix of science conceptions and misconceptions. Teaching science via multisensory experiences with live science phenomena also models the nature of science and contributes to memorable and transferable learning.

   The activities were selected to meet the six criteria of being safe, simple, economical, enjoyable, effective, and relevant for both teachers and their students (see Appendix A for a discussion of the criteria).

2. *"Visual participatory analogies"—that is, visual science education analogies—to catalyze the teacher-as-student's creative use of research-informed science education principles.*

   Teachers commonly use verbal analogies to help students understand new, unfamiliar science concepts in terms of more familiar, better-understood ones (e.g., the cell *is like* a factory). Unfortunately, teachers

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themselves are not typically provided similar conceptual scaffolds when they become students in science education courses or professional development programs. Visual participatory analogies are a new instructional strategy developed by the author for teaching education theory to teachers. With this strategy, teachers interactively participate with discrepant science phenomena in ways that metaphorically help them bridge the gap between science education theory and practice. For example, Activity #2 uses hands-on play with a Möbius strip as a visual participatory analogy for the interactive nature of teaching and learning.

Your participation as teacher-as-learner-experimenter (rather than simply passive reader) in these minds-on activities will lead you to question, and help you to revise, your implicit assumptions about the nature of science, teaching, and learning. At the same time, you will develop expertise with activities that you can use with your own students. The dual-purpose activities thus allow you to unlock two doors with one key—the doors to your own learning and to your students' learning.

At this point, if you have a burning desire for a direct experience with this science content–science education approach, go directly to a sample activity (e.g., Activity #3, "Burning a Candle at Both Ends: Classrooms as Complex Systems") right now and read the remainder of this Introduction after you have worked and played through the activity. *This book does not need to be used in a strictly linear, front-to-back sequence with your students.* Alternatively, you can read this Introduction (which also describes the book's organizational structure and the activity format), review the related research cited in the Appendixes, and then proceed to activities #1 and #2. These first two activities are introductions to the use of analogies and the idea of interactive teaching and learning that are featured in all subsequent activities.

This book attempts to bridge the gaps between scholarly cognitive science education research, national standards, and teacher-friendly activity books. It asks you to alternate between the roles of student-learner and teacher–reflective practitioner. I hope you will have as much fun with these dual-purpose activities as I have had in developing them during the course of my many years of working with teachers. A second volume is currently under development.

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Ways to Use This Book

Preservice Science Methods Courses

This book can be used in preservice science methods course as a supplement to middle and secondary methods textbooks that convey information about constructivist teaching. I believe that every methods class should be a lively, do-as-I-do exemplar of science inquiry approaches. As such, this book's 33 discrepant-event activities (and over 100 extension activities) can be modeled by the instructor and used both in student-presented microteaching lessons and as a resource for fieldwork experiences and student teaching. The science education analogy associated with each activity can be discussed in the methods class and further explored in online forums to emphasize learning as an act of minds-on cognitive construction.

Grades 5–12 Science Classes

Teachers in grades 5–12 science classes can read, practice, adapt, implement, videotape, self-analyze, and further refine the book's model science inquiry lessons. The science content information and science education analogy associated with each activity provide a broad context for the theoretical foundation of minds-on science teaching. Rather than merely being another source of neat activities to add to one's bag of tricks, this book is designed to encourage teachers to critically examine some of their own favorite activities to see how to increase the activities' inquiry potential or how to connect the activities to "big ideas" and scientific habits of mind.

Professional Development for Teachers

This book can also be used in collaborative, teachers-helping-teachers professional development. Whether you are a preservice, novice inservice, or veteran teacher, and whether you majored in science as an undergraduate or not, your own career-long, inquiry-based learning is essential to maintain your professional vitality. Increasingly, state and local school district policies and professional organizations such as the National Science Teachers Association are promoting and supporting continuous professional development (NSTA 2006, 2007a).

In fact, the professional development literature describes a wide variety of models for inservice teacher learning (Banilower et al. 2006; Loucks-Horsley et al. 1998; NRC 2001a; NSTA 2006, 2007a, 2007c; Rhoton and Bowers 2003; Yager 2005). Informal, one-to-one peer collaborations that share the wisdom of practice that resides in any school are too often an untapped resource for professional growth and curricular change. Pairs or small teams

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of teachers can use the activities in this book as starting points for informal "lesson study" (Stigler and Hiebert 1999). On a larger scale, with financial and logistical support from schools and districts, teachers in an entire science department could work together to refine one another's teaching by visiting one another's classrooms to model and critique lessons.

Other forms of professional development rely more on the leadership of a "master teacher." For instance, districts are increasingly supporting mentor–new teacher pairings and science specialist teachers to lead study groups. Additionally, grant-funded collaborations with scientists and science teacher educators at the college level may provide funding and expertise for an academic year of Saturday Science Seminars, for summer institutes, and for specially targeted graduate-level courses.

Teachers are justifiably skeptical about one-shot workshops run by "outside experts," and research indicates that these workshops rarely result in much more than short-lived motivational boosts. That said, even these quick-fix presentations can serve a catalytic role if they are followed by job-embedded support that helps teachers transfer the lessons learned into their science classrooms.

Other Considerations

If this book is used in a professional development course or program, it is best if the majority of the teacher-learners experience the activity "live" before reading the activity. Inquiry-based science teaching is based on the premise that prematurely giving answers (before engaging the learners with phenomena that raise questions for them to explore) can kill curiosity and limit learning effort and outcomes (NSTA 2004). However, if used in a self-study context, some of the element of surprise will necessarily need to be sacrificed. Even here, individual teacher-learners are encouraged to attempt to answer the questions embedded in the activities—by actually doing the activity—before reading the answers, which are intentionally placed at the end of each activity.

Most activities can be modeled in 10–20 min. when used with teachers as model science inquiry lessons or as science education analogies. With 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, completing and processing the activities could take up to a full class period and would optimally be placed in an integrated instructional unit of related concepts and activities that would extend over a 1–2 week period (e.g., using the 5E Teaching Cycle: Engage, Explore, Explain, Elaborate, Evaluate; see Appendix B for a discussion of this teaching cycle).

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Organizational Structure of the Book

This book's 33 interactive, experiential learning activities are clustered into three sections, which are discussed below. Professional development specialists and college-level science teacher educators may wish to use the activities as a framework for either a series of professional development sessions or a more formal course. The major theme of the nature of science, teaching, and learning as informed by cognitive science research runs through all the activities (Aicken 1991; Bybee 2002; Cocking, Mestre, and Brown 2000; Lederman 1992, 1999; McComas 1996; Michaels et al. 2008; NRC 2007; NSTA 2000). The individual activities also can be used as independent stand-alones. Individual science teachers not affiliated with a course or professional development program may wish to use the special Science Content Topics section (pages 361–365) to select activities that match their grades 5–12 instructional scope and sequence. In this case, the science education themes will be encountered on a need-to-know basis in the course of regular classroom teaching.

Section 1. Introduction to Interactive Teaching and Experiential Learning

This short, foundation-setting section (activities #1–#3) introduces analogies as a cognitive tool and instructional strategy for interactive teaching and learning. The three activities use science education analogies to challenge teachers to consider alternative ways of seeing their relationship with learners and to consider the power of inquiry-oriented, curriculum-embedded assessment.

Activity #1 is the only one in the book that is *not* framed around a discrepant-event activity (although teachers may want to adapt the activity to teach their students about the complementary roles and responsibilities of teachers and students). It provides a concrete example and model of how to effectively use analogies to help learners to construct well-articulated understandings and avoid generating misconceptions. References are provided to support teachers' ongoing use of analogies to help students understand nonobservable, abstract, or otherwise conceptually difficult science concepts in terms of more easily visualized, familiar phenomena and processes. Activity #2 introduces the idea of interactive, hands-on explorations (HOE) via a simple paper-and-pencil puzzle that asks learners to predict-observe-explain (POE). Activity #3 demonstrates how guided inquiry can uncover the science behind simple magic tricks.

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Section 2. Human Perception as a Window to Conceptions

These four activities (#4–#7) each include a number of mini-investigations that encourage learners to playfully explore some of the strengths and limitations of human perceptions (i.e., seeing, hearing, tasting, smelling, and heat flow and pressure-sensitive touching). Humans perceive, process (i.e., reconstruct and conceive), retain, and retrieve only the small portion of external reality that their sensory systems have evolved to detect, based on the selective, adaptive advantages provided (i.e., we notice on a "need-to-notice" basis). Also, to some extent, we perceive what we expect to perceive based on past experiences and preconceptions; human observations are always somewhat theory-laden. As such, our senses can be viewed analogically as tinted or foggy windows that allow small segments of filtered, external reality to enter into human consciousness and form the raw material for our conceptions (and possible misconceptions) about the nature of reality. Understanding our species-specific sensory limitations and individual attention deficits and learning how to design and use technology to help us extend the range, sensitivity, and reliability of our perceptions are central to the nature, history, and ongoing evolution of science that relies on valid, reliable, and "unbiased" empirical evidence.

Section 3. Nature of Cognition and Cognitive Learning Theory

Four major principles of cognitive learning theory are experientially developed through the 26 activities (#8–#33) that make up this major section of the book.

1. Knowledge transmission and passive reception models of teaching and learning are "unquestioned answers" that underlie common schooling practices that overemphasize teaching as telling and learning as listening (Michael and Modell 2003). By contrast, the research-validated idea of learning as a minds-on act of cognitive construction has the power to transform science education. Three hands-on explorations (activities #8–#10) are used to challenge outdated learning theories and provide multisensory experiences that support a more learner-active, constructivist model of understanding (which is further developed in subsequent activities).

2. Learning is a psychologically active, inside-out and outside-in process that is built on two-way interactions between and among individual minds and external learning environments. As such, learning depends on unique intrapersonal factors, interpersonal interactions (i.e., teacher ←→ learners and learners ←→ learners), and intentionally designed educational contexts. Effective teaching activates learners' attention and catalyzes cognitive

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processing. This general idea is introduced with two activities (#11–#12) and then experientially expanded on in the form of seven approaches that teachers can use to increase their pedagogical powers and instructional effectiveness (14 activities; #13–#26). These seven approaches might be viewed analogically as "weapons of mass instruction" that create pedagogical shock and awe to cause learners to pause, perceive, and ponder:

- Novelty/Changing Stimuli (activities #13–#14)
- Puzzles and Discrepant or Counterintuitive Events (activities #15–#16)
- Cognitive Connections and Meaningfulness (activities #17–#18)
- Multisensory Experiences and Multiple Contexts (activities #19–#20)
- Emotional Engagement, Connections, and Relevance (activities #21–#22)
- Adequate Time for Learning (activities #23–#24)
- Psychological Rewards (Gain/Pain or Benefit/Cost Ratio) (activities #25–#26)

3. Learners' prior knowledge (including preconceptions and/or misconceptions) and cognitive inertia (or "conservatism") may play a constructive, foundational role or a restrictive, limiting role relative to conceptual changes. Just as a solid house cannot be built on a weak foundation, new mental constructions will only stand the test of time if they are built on solid conceptual antecedents. Effective teachers activate and diagnostically assess learners' preinstructional understanding to check for valid precursor ideas, experiential and conceptual holes, and misconceptions. Although many new ideas can be readily assimilated in the context of preexisting ones, new knowledge often requires conceptual accommodation whereby the learners' prior conceptual networks must change for the new information to fit into the picture and make sense (activities #27–#29).
4. Effective science instruction catalyzes cognitive construction and builds a foundation for more independent learning by inviting inquiry rather than by indoctrinating. The last four activities (activities #30–#33) recapitulate the book's major theme of interactive teaching-learning that supports learners' active, minds-on cognitive construction. FUN and MENTAL activities that *engage* learners with discrepant phenomena, raise questions for *exploration* that demand *explanation*, and are rich in possibilities for *elaboration* are a powerful means of achieving this objective.

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Format Used in Each Activity

Each of the 33 activities has the following format.

Title
This is intended to forecast the science content and science education content foci of the activity.

Expected Outcome
This section is a short description of the setup and expected result of the activity.

Science Concepts
This section briefly discusses the science concepts exhibited by the discrepant event. The author assumes that teachers reading this book are at least somewhat familiar with the underlying science concepts; will develop a deeper understanding through the inquiry questions and answers built into the Procedure and Debriefing sections; and/or can readily obtain additional background information via the Extensions and Internet Connections sections. The activities cut across physical, life, and Earth science concepts with an emphasis on foundational physical science concepts that lend themselves to shorter, mini-experiments and science education analogies. That said, over half of the activities contain a substantive link to biological analogies and applications (see Science Content Topics, pp. 361–365).

Science Education Concepts
When used with teachers (as the targeted learners), each discrepant-event science activity also serves as a visual participatory analogy—or science education analogy—for a science education principle. The intent is to create a common experiential foundation for subsequent collegial conversations and collaborations on the science and art of minds-on science teaching strategies. The long-range goal of the activities is to increase teachers' science content knowledge and pedagogical content knowledge *simultaneously* (Cochran 1997; Shulman 1986).

Having several different activities for each science education principle allows both for instructional flexibility and for key ideas to be introduced, reinforced, and extended in different learning contexts with different analogies. If time permits, experiencing and critiquing multiple analogies for the same science education principle will enable teachers to form a richer, triangulated understanding.* Alternatively, a given activity might be modeled in

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**Triangulate* refers to the advantage of using multiple methods or approaches to lead to rich, nuanced answers to a given question. Because any single analogy has its limitations in explaining a given target, when teachers use multiple analogies they help students to develop a more complete understanding of a given scientific concept than they would if only one analogy were used.

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a professional development program and teachers could be asked to test-out additional related activities in their classrooms before a second, follow-up session in which they critique and improve the activities.

Materials

This is a list of the required and optional materials needed to complete the activity. Many activities can be done as either an individual hands-on exploration or as teacher or participant-assisted demonstrations, depending on the availability of materials, the time constraints, and instructional setting (i.e., professional development versus grades 5–12 classrooms). Most of the activities use common materials, but *representative* suppliers (and costs) are cited to facilitate easy ordering in cases where unique science equipment or "toys" are used. Although the author has found the cited suppliers to be cost-competitive, no endorsement of particular companies is intended. Additionally, as all prices are subject to change, readers of this book are encouraged to check with the science supply companies used by their local school districts.

Points to Ponder

Each activity includes several powerful quotes from famous scientists, philosophers, or educators. Serious, sustained attention to the history and philosophy of science (HPS) in the K–12 curriculum is called for by research and policy documents (AAAS 1993; Matthews 1994; NRC 1996). Arguments for including more HPS in science courses include the following:

1. Cognitive development (i.e., the idea that a student's cognitive ontogeny at times recapitulates the history of science phylogeny with respect to limited applicability models and misconceptions)
2. The need for a science-and-technology-literate citizenry that understands the nature and evolution of science
3. The benefits of situating and contextualizing science as a human endeavor that both affects and is affected by multicultural, historical forces

Brief historical quotes cannot do justice to HPS, but they can serve as catalysts to teachers to explore other HPS resources (e.g., Asimov 1976; Hakim 2004, 2005, 2007; Hellemans and Bunch 1988; Gribbin 2002; Silver 1998). The discussion questions in the Debriefing sections are explicitly linked to the quotes to raise HPS awareness and interest.

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Procedure

This section includes the functional description of one or two possible ways of doing the activity. As needed, separate descriptions are provided for two settings: "When Working With Teachers" (i.e., teachers experiencing the activity as professional development or as preservice teachers) and "When Working With Students" (i.e., in grades 5–12 classrooms). The sample inquiry questions typically include attention to "big picture" unifying concepts or themes (drawn from the National Science Education Standards [NRC 1996] and the Benchmarks for Science Literacy [AAAS 1993]) that guide the learners to use empirical evidence, logical argument, and skeptical review to make and revise hypotheses about what is occurring and why. Meaningful learning occurs when teachers build on knowledge- and comprehension-type questions (e.g., What do you observe?) up to questions that require higher-order thinking skills associated with application, analysis, synthesis, and evaluation (e.g., How do you account for and apply the science underlying your observations?) (Anderson and Krathwohl 2001; Bloom et al. 1956).

The sample inquiry questions in this section and the Debriefing section are not intended to be used verbatim; rather, they suggest possible productive lines of inquiry and model the art of effective science questioning.

> Effective questioning that elicits quality responses is not easy. In addition to optimal wait time, it requires a solid understanding of subject matter, attentive consideration of each student's remarks, as well as skillful crafting of further leading questions. (NRC 2001b, p. 35)

Questions posed by the teacher serve multiple pedagogical purposes. They catalyze two-way teacher-student interactions that go beyond a simple sequence of teacher question (initiation) → student response → teacher feedback that serve to "move a lesson along." They also provide formative assessment to determine if students are "getting it" and the opportunity for clarifications and deeper probing of student conceptions. More important, teacher-initiated questions explicitly model for students how to ask their own scientifically productive questions that lead to fruitful, inquiry-based examination of phenomena by students and interactions among students. As such, the questions generated by students provide a window into their cognitive processing and evolving conceptions, perhaps even more so than their answers to teacher questions.

Additionally, student-initiated questions help students learn important metacognitive skills related to learning how to learn and to developing the

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intellectual dispositions and habits of mind of active, engaged learners. Together, teacher- and student-initiated questions create a collaborative classroom environment based on a shared dialogue of discovery.

Debriefing

This section describes some of the broader context and lessons-to-be-learned about the science education and the science content. As in the Procedure section, separate "When Working With Teachers" comments (focused on science pedagogical knowledge) and "When Working With Students" comments (focused on science content) are provided as needed. The comments may also provide additional tips for teachers when using the activity to teach science to their grades 5–12 students. If desired, the teacher debriefing questions can be used as "homework" and/or discussed via electronic learning communities in live professional development sessions (NSTA 2008).

Extensions

These are brief descriptions of related "what if I were to change…" activities for further exploration as time and interest allow. Given the limited time in professional development settings, the extensions are especially useful for independent self-assessment work by teachers to determine if they really "get it." The extensions also provide complementary activities that could be used to help design 5E Teaching Cycles or integrated instructional units for grades 5–12 science instruction (see Appendix B for a description of the 5E cycle). Also, when the science content connects with another activity in the book, the related activity is cited. *The Extensions increase the number of distinct science inquiry activities in this book to to nearly 120.*

Internet Connections

In this list, readers will find up-to-date links to a variety of supplemental web-based resources including the following:

- Video clips of similar or related demonstrations where teachers can watch another teacher perform the mechanics of the demonstration
- Animations and interactive simulations that teachers can use to help the students visualize science principles and processes that are at scales that are too small/large, too fast/slow, or too dangerous or expensive to be seen with the unaided eye or realistically manipulated by students. Some of these websites (e.g., *http://phet.colorado.edu*) contain extensive libraries of simulations and related teaching materials that cut across science disciplines.

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- Online encyclopedias that further explain the science content and related real-world applications
- Short professional development readings related to the science education analogy

E-learning experiences and resources represent an ever-growing venue for teacher professional development and "just-in-time" instructional resources for teaching K–16 science (NSTA 2008). The internet is in a continual state of flux, but the majority of the cited web pages originate from relatively stable, nonprofit organizations (e.g., museums, professional associations, and universities). In addition to these websites, each of which has been reviewed by the author for relevance to the activities in this book, teachers may explore the science content and related curricular materials more broadly through NSTA SciLinks (*www.scilinks.org*).

In either case, occasional encounters with "dead" links are the equivalent of a book or journal going out-of-print or otherwise becoming unavailable—*except* that in the case of the internet, other great resources are always beckoning a few keystrokes away. As such, the sites provided should be viewed as starting points for further explorations. In addition to their inclusion in the book, an NSTA Press online, hyperlinked resource will allow readers to electronically access the sites in spring 2010.

Answers to Procedure and Debriefing Questions

The answers to the questions in the Procedure and Debriefing sections are deliberately presented at the very end of each activity. This was done to maintain the inquiry nature of the book. Attempting to answering the questions in the context of doing the activity (rather than reading the answers first) will help the teacher enjoy the activity more, appreciate the challenge that inquiry questions pose for his or her own students, and improve the teacher's own questions and answers.

Conclusion

As teachers, we tend to teach both what and how we were taught during our "apprenticeships of observation" as K–16 students (Lortie 1975). It's great to be able to stand on the shoulders of our own exemplary, former science teachers, but research on how to facilitate learning is always advancing. As such, this book challenges you to "question the answers" of your own past experiences as students and to make a paradigm shift away from any

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pedagogical beliefs and practices that no longer make sense in the light of today's research-informed standards.

The National Science Teachers Association has long recognized reflection-in-action by "teacher action-researchers… [as the] basis for curricular and instructional reform" (NSTA 1990; see also Schön 1983). The authors of the National Science Education Standards (NRC 1996) concur:

> 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)

This book's combined science content–science education focus is designed to help current (or future) grades 5–12 science teachers, professional development specialists, and college-level science teacher educators achieve this standard.

The teacher is the key to change and learning in the classroom (NCMST 2000; NCTAF 1996, 1997; NSB 2006; NSTA 2007a). In fact, "the single most important factor affecting student academic gain is teacher effect" (Sanders and Rivers 1996). Some science teachers mistakenly believe that factors outside their control—such as family income, parent education levels, and race or ethnicity—are acceptable explanations for many of their students failing to learn science. On the contrary, effective teachers can cumulatively have a greater impact on educational outcomes than those factors (Ferguson and Ladd 1996). Specifically, the use of engaging activities in every science class is an example of something that *is* in the teacher's control as is teacher collaboration in continuous professional development.

The book is the result of mutually beneficial interactions I have had with hundreds of dedicated science teachers over the last 30 years (e.g., O'Brien 1992a, 1992b; Stamp and O'Brien 2005; Stannard, O'Brien, and Telesca 1994). Please use, improve, and share these activities with your colleagues and students. I hope that you find this book to be "edu-taining" in ways that extend well beyond the initial surprise value and motivational impact of the individual activities. The best teaching and learning experiences are about sharing, catalyzing change in others, and being changed in the process.

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Science Education Topics

This book has two focuses—science education and science concepts. The author has designed two alternative tables of content—in addition to the traditional one on pages v–vi—that are organized by these two focuses. The table of contents that begins on this page is organized by science education topics; the table of contents organized by science concepts begins on page 361.

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.

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: The activities use an inquiry-based instructional sequence.

PPP: Paper and Pencil Puzzle: The 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.

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Science Education Topics

Section 1. Introduction to Interactive Teaching and Experiential Learning

Activity	Activity Type	Science Concepts
1. Analogies: Powerful Teaching-Learning Tools	MIX/PPP p. 3	analogies as conceptual tools (*This is the only activity that is not a science discrepant event.*)
2. Möbius Strip: Connecting Teaching and Learning	HOE/PPP p. 15	NOS, POE, topology
3. Burning a Candle at Both Ends: Classrooms as Complex Systems	TD p. 25	POE, phase change, combustion, convection, density, cellular respiration (Extension #3: BIO)

Section 2. Human Perception as a Window to Conceptions

4. Perceptual Paradoxes: Multisensory Science and Measurement	PAD p. 37	sensory adaptations and survival (BIO), (mis)perception, cognition, temperature sensitivity, taste (as related to smell), weight versus density
5. Optical Illusions: Seeing and Cognitive Construction	PPP p. 47	sensory (mis)perception, cognition (BIO); quantitative measurements
6. Utensil Music: Teaching Sound Science	HOE p. 63	sound transmission, perception, sensory variations in species (BIO)
7. Identification Detectives: Sounds and Smells of Science	HOE/MIX p. 73	BBS, NOS, sensory adaptations, survival (BIO), identification by sound, identification by smell

Section 3. Nature of Cognition and Cognitive Learning Theory

Knowledge Transmission and Reception Versus Construction of Understanding

8. Two-Balloon Balancing Act: Constructivist Teaching	HOE or PAD p. 87	NOS, POE, LaPlace's law and surface tension, air pressure, BIOmedical applications (Extension #2)
9. Batteries and Bulbs: Teaching Is More Than Telling	HOE p. 97	complete or closed electric circuits, energy conversions
10. Talking Tapes: Beyond Hearing to Understanding	HOE p. 109	TOYS, sound, information encoding and gene expression, form/function relationships (BIO)

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Activity	Activity Type	Science Concepts
Learning as a Psychologically Active, Inside-Out, and Outside-In Process		
11. Super-Absorbent Polymers: Minds-on Learning and Brain "Growth"	HOE or PAD p. 119	measurement, polymers, TOYS, BIO/evolution, STS tradeoffs, perspiration (Extensions #2 and #4)
12. Mental Puzzles, Memory, and Mnemonics: Seeking Patterns	PPP p. 131	NOS, pattern recognition, cognition (BIO)
*Novelty and Changing Stimuli**		
13. Sound Tube Toys: The Importance of Varying Stimuli	HOE or PAD p. 141	sound energy, pitch, Bernoulli's principle, TOYS, POE, animal BIOadaptation of noticing novelty
14. Convection: Conceptual Change Teaching	PAD p. 153	heat, equilibrium, density, convection, POE
*Puzzles and Discrepant or Counterintuitive Events**		
15. Brain-Powered Lightbulb: Knowledge Transmission?	PAD p. 163	complete or closed electric circuit, BIOfuels analogy (Extension #1), TOYS
16. Air Mass Matters: Creating a Need-to-Know	TD p. 171	air pressure, inertia, POE
*Cognitive Connections and Meaningfulness**		
17. 3D Magnetic Fields: Making Meaningful Connections	TD p. 179	magnetism, force field lines, neural networks, MRI (BIO/Extension #1)
18. Electric Generators: Connecting With Students	PAD p. 189	electric generators ←→ motors, electric circuits
*Multisensory Experiences and Multiple Contexts**		
19. Static Electricity: Charging Up Two-by-Four Teaching	PAD p. 201	static electricity (triboelectricity)
20. Needle Through the Balloon: Skewering Misconceptions	HOE or PAD p. 211	polymer elasticity, cell membrane model (BIO/Extension #1)
*Emotional Engagement, Connections, and Relevance**		
21. Happy and Sad Bouncing Balls: Student Diversity Matters	HOE or PAD p. 221	TOYS, POE, potential→kinetic conversion, law of conservation of energy, friction, elasticity, form/function fitness (BIO)

(continued)

*Each of the categories with an asterisk is one of the Seven Principles for Activating Attention and Catalyzing Cognitive Processing (Activities #13–#26). The seven principles have been identified by the author.

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Science Education Topics

(continued)

Activity	Activity Type	Science Concepts
22. Electrical Circuits: Promoting Learning Communities	HOE or PAD p. 233	complete or closed electric circuits, energy conversions, TOYS
*Adequate Time for Learning**		
23. Eddy Currents: Learning Takes Time	PAD p. 241	electromagnetism, Lenz's law
24. Cognitive Inertia: Seeking Conceptual Change	TD/PAD p. 251	Inertia and cognitive conservatism, independence of vertical and horizontal forces and motions
*Psychological Rewards (Gain/Pain or Benefit/Cost Ratios)**		
25. Optics and Mirrors: Challenging Learners' Illusions	PAD p. 259	optical illusions, mirrors, BBS, NOS, TOYS
26. Polarizing Filters: Examining Our Conceptual Filters	TD p. 267	light polarization, UV protection for skin and eyes (BIO/Extension #1)
Role of Prior Knowledge, Misconceptions, and Cognitive Inertia		
27. Invisible Gases Matter: Knowledge Pours Poorly	PAD p. 275	gases occupy space (volume)
28. The Stroop Effect: The Persistent Power of Prior Knowledge	PAD/PPP p. 285	NOS, human perception, cognition (BIO)
29. Rattlebacks: Prior Beliefs and Models for Eggciting Science	HOE or TD p. 293	BBS, NOS, TOYS, energy conversion, rotational inertia, model of the lithosphere
Science Instruction Catalyzes Cognitive Construction		
30. Tornado in a Bottle: The Vortex of Teaching and Learning	PAD p. 301	gases occupy space, POE, TOYS
31. Floating and Sinking: Raising FUNdaMENTAL Questions	HOE p. 309	density/buoyancy, diffusion, osmosis (BIO), nucleation sites, solubility of gases in liquids, NOS, POE
32. Cartesian Diver: A Transparent But Deceptive "Black Box"	HOE p. 321	Archimedes and Pascal's principles, Boyle's law, density/buoyancy, BBS, NOS
33. Crystal Heat: Catalizing Cognitive Construction	TD/HOE p. 331	phase changes, latent heat, law of conservation of energy. BIO: cellular respiration (Extension #2), perspiration and thermoregulation (Extension #4), bee colony collapse disorder (Extension #5)

*Each of the categories with an asterisk is one of the Seven Principles for Activating Attention and Catalyzing Cognitive Processing (Activities #13–#26). The seven principles have been identified by the author.

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Activity 16

Air Mass Matters:
Creating a Need-to-Know

Expected Outcome

A flat pinewood stick (or other soft wood) is placed under several sheets of newspaper and extended over the edge of a table. It snaps when quickly struck, without lifting or tearing the paper.

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Science Concepts

Air has weight and exerts a pressure of 10 N/cm^2 (or 14.7 lbs/in^2) at sea level. Gases are not "no thing." Gases have mass, occupy space, exert pressure, and are composed of molecules separated by truly "empty" space. Inertia, or the tendency of a body at rest to stay at rest, is also a relevant factor in this experiment.

Science Education Concepts

Teachers sometimes need to initially take familiar (and therefore unnoticed) things and make them strange so that they can become familiar again but—the second time around—understandable. Discrepant or counterintuitive events activate learners' attention and catalyze cognitive processing by creating need-to-know motivation. This demonstration serves as a *visual participatory analogy* in the sense that students/sticks can only successfully lift the conceptual weight or load of a given educational task if the instructional pace (or speed) that they are expected to move at is within their zone of proximal development or ZPD (i.e., what the learner can achieve based on prior knowledge and abilities with the scaffolding provided by a carefully targeted instructional sequence and a supportive teacher). In the case of this demonstration, if the teacher pushes the student/stick at a too fast a rate, it breaks. If the teacher wants to avoid breaking the student/stick, he or she needs to use a slow, deliberative pace rather than a forceful, quick pass through too many topics in too little time (see Internet Connections: Wikipedia: Cognitive load theory and ZPD).

Materials

- Flat pinewood stick (e.g., cheap yardstick or extra long [2 ft.] paint stick) and several sheets of newspaper

Safety Note

Students and teacher should wear safety glasses or goggles during this activity.

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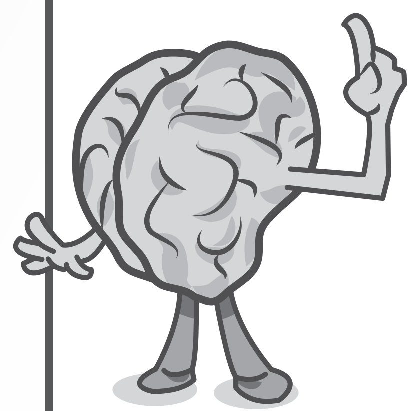
Points to Ponder

I do not mind if you think slowly. But I do object when you publish more quickly than you think.

—Wolfgang Pauli, German-American physicist (1900–1958)

When you believe you have found an important scientific fact, and are feverishly curious to publish it, constrain yourself for days, weeks, years sometimes, fight yourself, try and ruin your experiments, and only proclaim your discovery after having exhausted all contrary hypotheses.

—Louis Pasteur, French chemist and microbiologist (1822–1895)



Procedure

(See answers to questions in steps #1–#4 on p. 177.)

1. Place the pinewood stick on a table with about 10 cm (4 in.) extending over the edge. Ask: What would happen if I were to strike the extended end of the wood? Do this experiment.
2. Repeat the experiment, except this time place two, full sheets of standard-size newspaper on top of the portion of the wood stick that rests on the tabletop, taking care to smooth out the newspaper and press it down firmly against the tabletop. If this is not done and a significant air pocket resides under the paper, the demonstration will not work consistently as intended due to an equalization of air pressure above and below the paper. Again, ask the learner to *predict* what will happen when you rapidly strike the extended portion of the stick.

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3. Ask questions such as the following:
   a. What did you *observe* in this second case and how can you *explain* the difference between these two trials?
   b. What would happen if I placed the wood stick on the table without the newspaper and had someone press down on the portion that rests on the table while I strike the extended portion?
   c. What would happen if I used the newspaper again, but rather than striking the stick, I slowly pressed down on it?
   d. How do these extra tests provide clues as to how to explain the demonstration in which the stick breaks?

Any of these variations can be repeated with new sticks (or by extending the stick if it is long enough).

4. Depending on where this activity is used in a 5E science unit (i.e., Engage versus Explain or Elaborate; see Appendix B for a discussion of the 5E Teaching Cycle) and the grade level, the teacher may have students calculate the effective weight of air that is pressing down on the surface area of a single piece of newspaper.

Debriefing

When Working With Teachers

In a discrepant-event demonstration, the teacher takes something that is typically unnoticed by students (e.g., air pressure) and makes them pause, perceive anew, and ponder on this thing (i.e., it activates their attention). Discuss the pedagogical advantages of using the phenomena-before-facts or the wow-and-wonder-before-words approach over the common (reverse) approach in which the teacher starts with lecture notes or gives a reading assignment on air pressure. Teachers can explore the large body of published research on student misconceptions about gases, air, and pressure (e.g., see Driver et al. 1994; see chapters 9 and 13 for overviews).

The demonstration serves as a visual participatory analogy for how the cognitive load of a given educational task or learning objective—as perceived by students—depends, in part, on the speed of instruction. Rushing through big ideas too quickly can "break"

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students, whereas a slower, more deliberate approach is much more likely to succeed. The contrasting quotes on page 173 can focus learners' attention on the nature of science (i.e., empirical evidence, logical argument, and skeptical review) and can help them contrast the relative checks on truth in the popular press versus such checks on scientific journals.

The best science teaching is more about inspiring inquiry than indoctrination in "received truth." Similarly, if students are going to be asked to calculate the weight of air pressing down on the paper, it is important that the teacher first create a context that catalyzes learners' curiosity—rather than present calculations in no context at all, an approach that will kill curiosity.

When Working With Students

After students do other related activities—such as the Extensions and activities found on websites listed in Internet Connections—that make the unnoticed effect of air pressure "sensible," the teacher should introduce the basic facts about air pressure discussed in the Answers to Questions in Procedure, step #3 on p. 177.)

Extensions

1. *The Crushing Soda "Pop" Can*. This discrepant event is a variation of an old demonstration. A little water placed in an empty 1 gal. rectangular metal can is brought to a boil and the can is then removed from the heat and tightly capped. As the can cools, the water vapor condenses and leaves a partial vacuum inside the sealed can that then collapses under the now greater, external atmospheric pressure. With a soda can, just cover the bottom of the empty can with water, boil it to drive out air, and fill the can with water vapor. Then either cap the can with a fizz-saver lid or turn the can upside-down on top of a container of water. In the latter case, the can will rapidly crush and partially fill with water. (See Internet Connections: Purdue University, among other websites, for explanations.)

   Alternatively, a vacuum pump causes the reverse expansion effect by decreasing external pressure on a partially sealed, air-filled container (e.g., a balloon, a marshmallow, or shaving cream) that is under an evacuated, airtight chamber.

Safety Note

The edges of metal cans can be sharp and can cut the skin. Handle with caution.

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2. *Air Mass Matters.* Place two identical, uninflated balloons on a double-pan balance. (See safety issues regarding latex balloons on p. 89. Avoid latex balloons.) They will balance. If one of the balloons is then inflated and tied off, the balance will tip in direction of that balloon, indicating that air has mass. Similarly, a teacher can demonstrate that if a deflated sports ball is weighed and subsequently pumped up with air, the mass gain is directly proportional to the number of pumps. Alternatively, this can be done on a smaller scale as a hands-on exploration by using fizz-saver caps and a 2 L empty soda bottle. (*Note:* P1-2050/Individual Pressure Pumper can be purchased from Arbor Scientific for $3.25 or from local stores as a device to save the fizz on opened soda bottles). In either case, you may want to use temperature strips on the plastic bottle to also study the relationship between pressure and temperature.

Internet Connections

- Arbor Scientific's Cool Stuff Newsletter: *www.arborsci.com/CoolStuff/Archives3.aspx.* (See Chemistry: Gas laws smorgasborg and Pressure and fluids demonstrations.)
- Can Crush Demo/Railroad Tank Car Crush: *www.delta.edu/slime/cancrush.html*
- HyperPhysics, Department of Physics and Astronomy, Georgia State University: Select Video/Demos: Fluids: Liquids and gases: Atmospheric pressure: *http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html*
- Purdue University: Can crusher: *http://chemed.chem.purdue.edu/genchem/demosheets/4.8.html*
- University of Iowa Physics and Astronomy Lecture Demos. *http://faraday.physics.uiowa.edu* (See Heat and fluid: Atmospheric pressure demonstrations: Crush the can, crush the soda can; Magdeburg hemispheres; Water column-water barometer; Suction cups-rubber sheets; Stick and newspaper and the vacuum cannon.)
- University of Virginia Phun Physics Show: *http://phun.physics.virginia.edu/demos* (See Bell jar/shaving cream in vacuum; Collapsing drum; Magdeburg hemispheres; Marshmallow man.)

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- Wake Forest University: Physics of matter: Pressure demonstration videos: *www.wfu.edu/physics/demolabs/demos/avimov/bychptr/chptr4_matter.htm*
- Whelmers #21 Balloon (in Bottle) Vacuum: *www.mcrel.org/whelmers/whelm21.asp*
- Wikipedia: Cognitive load theory: *http://en.wikipedia.org/wiki/Cognitive_load_theory* and Zone of proximal development: *http://en.wikipedia.org/wiki/Zone_of_Proximal_Development*

Answers to Questions in Procedure, steps #1–#4

1. The wood flips in a somersaulting motion just as most people would predict.
2. A likely response will be that the stick will again fly up but that this time the stick will either take the paper with it or rip the paper.
3. When the newspaper is placed over the wood, the wood breaks right at the edge of the table if the demonstrator strikes hard rather than slowly pressing down on the wood. In the latter case, the newspaper is lifted up. By smoothing the paper firmly against the table and removing air from underneath, you create a situation where the wood sticking up is pushing against the weight of a column of air that extends to the outer limits of the Earth's atmosphere. Inertia causes the paper to remain at rest and the rapidly moving end of the stick to keep moving, which it does by snapping at the point where it extends just beyond the table. Conversely, if the wood stick is pushed down slowly, the air that seeps in underneath the paper can exert pressure upward to counterbalance the air pressure on top of the paper and the stick can easily lift the paper up without snapping. The relevant explanatory facts are as follows: air pressure = force/area = weight of the column of air/surface area. At sea level, air pressure = 10 newtons/cm^2 or 14.7 lbs/in^2. (*Note:* 10 N = weight of a 1 kg mass at sea level.)
4. The calculation of the effective weight of the column of air that is pressing down on the surface area of a single piece of newspaper is as follows: surface area = 61 cm × 53 cm = 3,233 cm^2 and weight = 3,233 cm^2 × 1 kg/cm^2 = 3,233 kg (technically, kg is a unit of mass, not weight) or nearly 7,113 lbs!

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