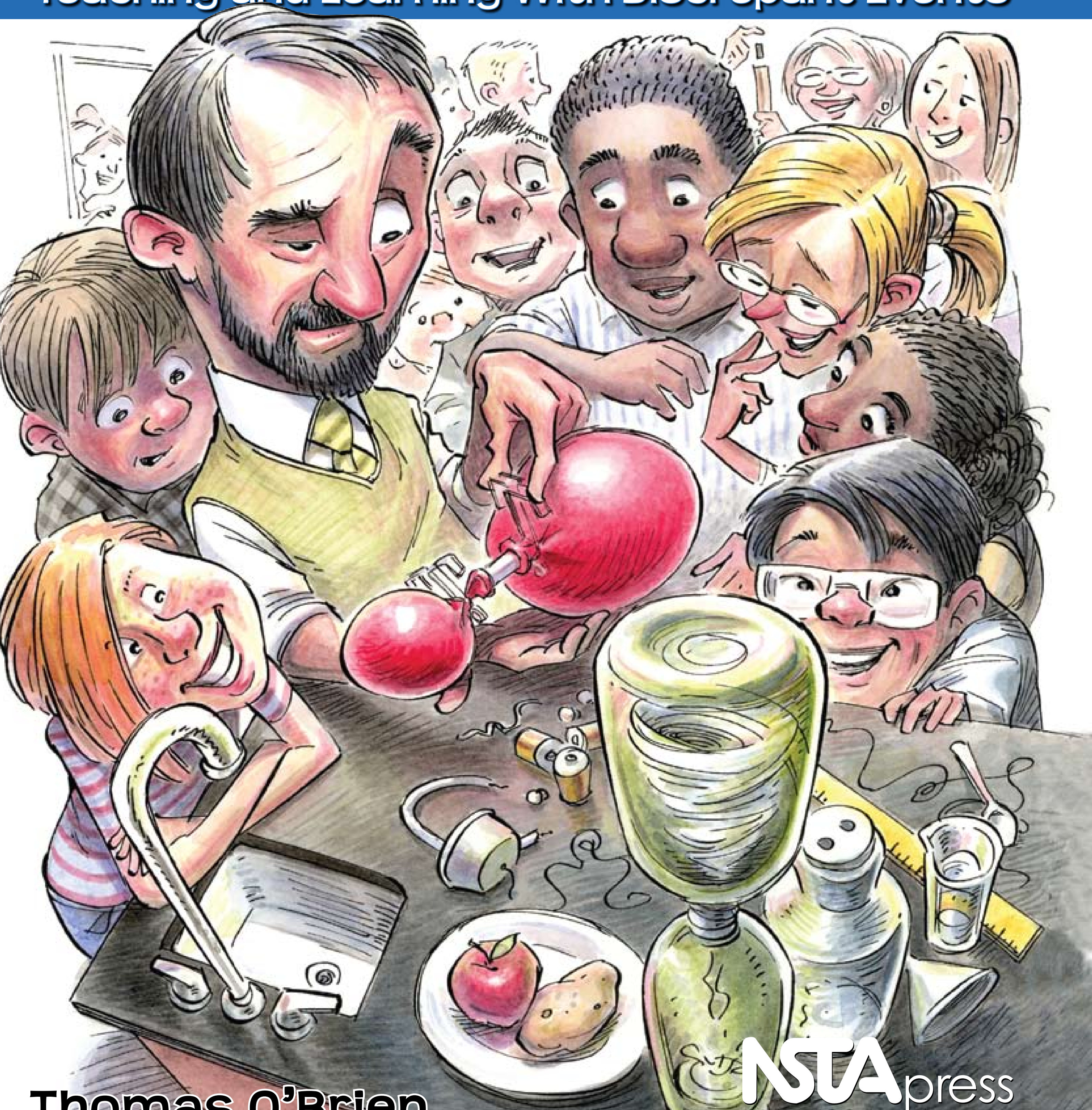
Brain-Powered Science

Teaching and Learning With Discrepant Events



Thomas O'Brien

NSTA press
National Science Teachers Association

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National Science Teachers Association
Arlington, VA

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About the Cover—Safety Issues: In the cartoon drawing on the cover, artist Dan Vasconcellos depicts the energy and excitement present in a school science lab. During actual school lab investigations, students should always maintain a safe distance from the teacher who is doing the demonstration (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)

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.

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.

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

> 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.

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 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).

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.

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

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.

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.

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.

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 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.

- 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 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.

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.

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)

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)

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*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.

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**

Activity	Activity Type	Science Concepts
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)**

Activity	Activity Type	Science Concepts
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

Activity	Activity Type	Science Concepts
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

Activity	Activity Type	Science Concepts
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)

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*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.

Activity 7

Identification Detectives: Sounds and Smells of Science

Expected Outcome

The topic of sound is introduced via a mixer activity that involves finding one to three people in the class who have the same "black box system"—an opaque plastic canister—based on how the canister sounds (and feels) when shaken. A similar activity can be done using the sense of smell (see Extensions).

Science Concepts

Sound energy is produced as a mechanical vibration that is transmitted as a longitudinal or compression wave from particle to particle through a medium. The activity serves as a concrete example of and *visual participatory analogy* for the work of scientists who sometimes encounter black box systems that they cannot open and peer inside (given current technologies). In such cases, they make creative leaps of imagination to infer internal composition based on indirect observations and measurements (i.e., empirical evidence), logical arguments, and skeptical review. (See Materials for the optional use of balances to assess students' prior skills with massing objects and to emphasize the quantitative nature of "sound" science. This activity and a related Extension variation on smell can be used in life science classes to begin a unit on the evolution and selective adaptive advantages of sensory perceptual systems.)

Science Education Concepts

This simple, hands-on exploration can be used to emphasize the role of sensory perception as a necessary antecedent to mental conception, the nature of science, and the pedagogical value of a "fun phenomena first" or "wow and wonder before words" instructional strategy. As a mixer, it has students form learning groups by identifying other students with the same "black box." The mixer is a good introduction to a unit on sound. While most hands-on explorations emphasize the sense of sight, this one depends on sound and touch (or smell). It also demonstrates that musical and bodily-kinesthetic intelligences are differentially distributed among students.

Safety Notes

1. Students and teacher should wear indirectly vented chemical splash goggles during this activity.
2. Use caution when handling sharps (e.g., pins, tacks, and screws) that can puncture or cut the skin.

Materials

- 1 35 mm canister or other comparably sized, plastic opaque bottle for each learner. Digital photography is making it harder to obtain free 35 mm canisters from photography stores. They may be purchased from science suppliers such as the following:
  - Arbor Scientific. *www.arborsci.com* 800-367-6695. film canister/PX 1028. $0.75 each

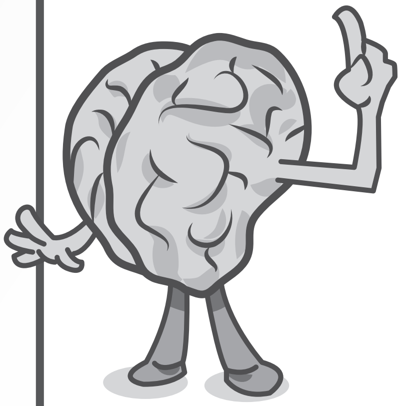
- Educational Innovations. *www.teachersource.com* 888-912-7474. surplus film canisters/CAN-150. $12.95 (~40 canisters)

Alternatively, clean, empty, opaque, nonprescription pill bottles of uniform size will also work.

- *Optional:* If desired, balances can be used to determine the mass of the canisters as an additional piece of verifying information on the match between any two samples. Also, magnets could be made available to determine if any of the hidden contents are magnetic. Water containers can be used to determine the containers' floating orientation based on density. It is also possible to assemble two sets of canisters that have the same mass (and perhaps even sound similar) that would have different magnetic properties. This simple activity can be made just a little more complicated than shaking a wrapped birthday gift to guess its contents or as challenging as a model-building laboratory experiment involving multiple items per canister or substances that change when shaken (e.g., a small quantity of liquid soap water that reversibly forms gas-filled soap bubbles).

Points to Ponder

> *So little done, so much to do [his last words].*
>
> —Alexander Graham Bell, Scottish-American scientist-inventor and educator of the deaf (1847–1922)
>
> *They never will try to steal the phonograph. It is not of any commercial value.*
>
> —Thomas Alva Edison, partially deaf American inventor (1847–1931)



Procedure

Pre-Class Preparation: Divide the canisters into groups as large as the desired size of your cooperative learning teams (i.e., two–four). Use number or letter labels to identify each canister so you can keep track of the contents of the canisters without having to remove the lids. Do NOT have matched sets listed in an order identifiable by the learners. Put equal amounts or numbers of identical objects in each group of matched canisters. Use a variety of household materials to make the desired number of sets of canisters. Sample items to use include BBs, buttons, cotton balls, lentils, marbles, paper clips (metal and plastic), pennies, washers, small screws, iron fillings, puffed cereal, pushpins, rice, road salt, sand, sugar, sunflower seeds, and thumbtacks. More careful discernment will be needed if multiple canisters contain different numbers of the same items (e.g., one group has two pennies and another group has three pennies).

1. Randomly distribute a sealed canister to each student and instruct the students to "shake, rattle, and roll" (but NOT open) their "black boxes" to become familiar with the sounds the canisters make when treated in specific ways. Learners then circulate around the classroom to compare the sounds of their canisters with those of their peers to find two or more buddies with containers that sound as if they all contain the same object. Emphasize that the canisters should not be opened at any time.

   When used as a mixer with teachers attending a professional development session: You may want to introduce the activity by asking teachers to share their names, one thing they'd like to learn about, one barrier they face in teaching minds-on science, and how they currently understand the two-way interactive nature of perceptions and conceptions.

   When used with students starting a unit on sound energy: Ask them to share one fact they know and one question they have about the science of sound. If these ideas are written down on index cards and collected, they serve as quick, preinstructional diagnostic assessments.

2. As the groups of students with the same sounds start to coalesce, encourage students to brainstorm indirect ways that they could gather more information about their canisters' unknown contents. Encourage cooperation among individuals who have not found their matches, and, if necessary, use your answer key to help individuals who have not yet found their groups or provide balances to help students confirm the groups to which they belong. If time is available, the teacher can provide a broad range of materials, along with empty canisters, for the groups to attempt to build a model that has the same properties and behaviors as the unknowns in their canisters.
3. Ask the small groups to discuss one or more of the following questions depending on whether the intended focus is on physical science, life science, or the nature of science:

(See answers to the following questions on p. 82.)

a. Did you find this activity challenging? If so, why?
b. Does all sound involve the vibration of matter? Can sound travel through a vacuum?
c. Is it easier to "prove" that two things are identical or that they are different? Why?
d. How does building a model of the system increase our confidence in our identification?
e. Why was the sense of hearing crucial to the survival of humans in prehistoric times and why is it also crucial in modern, nonindustrialized societies? How is (or was) the sense of hearing like and unlike the sense of sight? What challenges do the hearing impaired and deaf face in our modern society?
f. As a social species, what unique advantages do we have when it comes to cooperating?
g. How are the black box systems used in this activity similar to systems studied by scientists and engineers?
h. What real-world objects or processes cannot currently "be opened," and what new imaging techniques are allowing us to peer inside some of nature's black box systems?

Debriefing

When Working With Teachers

In addition to discussing any of the questions on page 77, challenge science teachers to consider ways they can increase the signal-to-noise ratio (S/N) of the audio components of their lessons—that is, how can they amplify the impact of their verbal messages to students in the midst of a classroom's background noise and distractions. Professional actors learn to intentionally vary their volume and pitch, as can teachers. (See Tauber and Sargent Mester 2007 for other nonverbal ways of increasing S/N. Also consider teaching students the skills of active listening.)

Our mental constructions (i.e., concepts and conceptual networks) are built from the foundation of our perceptions (i.e., environmental inputs through the selectively biased channels of our senses). In this sense, all observations are theory laden. By starting units with engaging activities that feature "fun phenomena first," teachers generate need-to-know questions that students will want to answer.

When Working With Students

This activity is a simple Engage-phase, hands-on exploration activity to be followed by more experiments on the science of sound (see activities #6 and #13). (Also see Appendix B for a description of the 5E Teaching Cycle, of which the Engage phase is a part.) Challenge students to consider how in our modern, sci-tech world, we are bombarded with sounds from traffic, construction, TV, the radio, and other sources, many of which bid for our attention, seek to alter our moods, get us to buy specific products, attend certain movies, and alert us of potential danger. Share the quotes from Bell and Edison, and challenge students to think about how the growth of scientific knowledge has allowed new generations of technologies to supplant landline telephones and phonographs with cell phones and digital recordings.

Extensions

1. *Odoriferous Olfactory Observations: The Nose Knows.* Learners use their sense of smell (rather than sound) to find their matches in the classroom and attempt to identify unknown substances.

Odoriferous solids or different smelling liquids dropped onto and absorbed into cotton balls can be used in canisters that have had small holes drilled into their tops to allow detection by sense of smell. Sample solids include spices and flavorings such as basil, black pepper, chili powder, cinnamon, cloves, garlic, ginger, ground coffee, mint leaves, nutmeg, oregano, and thyme. If using ground powders, place them in a fine mesh bag inside the canisters (or use the mesh and a rubber band to cover the opening of the canisters before securing the top) to prevent the powder from falling through the drilled holes. Sample liquids include extracts such as almond, banana, lemon, orange, peppermint, and vanilla and/or other liquids such as lavender oil, pickle juice, scented oils, and odorless water.

Demonstrate the wafting technique for smelling the contents of the canisters. If you wish to keep the canisters from cross-contamination for future use, store identical sets in separate plastic containers that are solid and sealed after completing the activity. (*Note*: Many odors can diffuse through plastic bags.)

In biology, a sense of smell was one of the earliest chemical detection systems to evolve. (Organisms notice smells on a need-to-know basis; the evolution of more complex nervous systems was driven by an "economic" reality of a kind of unconscious cost/benefit analysis.) Smell continues to play a major role in the survival of many animals whose abilities to detect as many as 10,000 different odors in very low concentrations greatly exceed those of humans. Plants have co-evolved to use odors to attract animals to aid in the plants' reproduction. Foods, toxins, and sexual mates may be identified by their chemical smell "signatures" and social communication is often linked to pheromones. While the role of pheromones in human sexual attraction is still being studied, perfume and cologne industries vie for consumer dollars with claims of producing the smell that will make the consumer irresistible to members of the opposite sex. (See Internet Connections: SFN, Mystery of Smell, and NOVA Online.)

2. *Termite Trails*. The fact that termites will track a continuous line made with a Bic Papermate pen and other common pens (but not markers, pencils, or simple grooves made in paper) makes for a

nice biological black box system. Students can discover that this behavior is related to smell rather than sight and color (see Internet Connections and the products found in science supply catalogs such as Ward's Termite Trails: Follow the Ink Lab Activity (Cat.# 87 V 3525. $32.50). Termite societies are organized into rigid castes: a few reproductives, a larger number of soldiers, and—the most numerous caste—the blind, sterile, 7–10 mm long workers. Using the worker termites in the classroom eliminates the risk of inadvertently creating an infestation if termites escape.

3. *Black Box Basics and Beyond.* See the Internet Connections for other teacher-built demonstrations and commercially available black box experiments that teach the nature of science and its reliance on empirical evidence, logical argument, and skeptical review. See also commercial applications of nondestructive testing (NDT).
4. *Silent Movies and Remember That Jingle.* Demonstrate the importance of sound in our multimedia world by playing a short video clip from an old silent movie, a modern movie, or a TV commercial with the sound off. Even if close captioning of dialogue is available, much of the emotional power and impact of a scary or action-packed scene or a great commercial is lost when the sound is muted. Challenge students to see how many ads, TV shows, or movies they can remember by the jingle, song, or instrumental music that accompanies them. Also, students can be taught to rewrite lyrics for popular tunes to help them use their musical memories to remember scientific information. Under Internet Connections, see the website Neuroscience for Kids for examples of "brain songs" that emphasize the idea of neural connections and meaning-making as linked to familiar tunes.
5. *Historical Connections*. Students can research the biographies of Bell and Edison, who were contemporaries of each other. Bell was a professor of vocal physiology and a teacher of the deaf; Edison, in addition to being a brilliant inventor, had profound hearing loss for most of his life (something he viewed as an advantage rather than a disability!). Both were highly inventive men who saw science as a means to improve the human condition. Edison even invented the idea of an "invention factory" to

systematically do research and development with the intention of creating commercial products (e.g., moving pictures and the phonograph) that would serve humanity and generate a profit. Still, as the quote shows, he underestimated the value of his phonograph in creating a worldwide music industry.

Internet Connections

- American Educator (see also *www.danielwillingham.com* for other articles and videos): Do visual, auditory, and kinesthetic (VAK) learners need VAK instruction?: *www.aft.org/pubs-reports/american_educator/issues/summer2005/cogsci.htm*
- Doing Chemistry (movies of demonstrations): Mystery boxes: *http://chemmovies.unl.edu/chemistry/dochem/DoChem001.html*
- International Mind Brain and Education Society: *www.imbes.org*
- Lab-Aids Inc.: Ob-Scertainer® A Better Black Box, Kit No. 100, $69.95/24 students: *www.lab-aids.com/catalog.php?item=100*
- Magic Water Black Box Activity: *www.scienceteacherprogram.org/genscience/Chien05Lesson/INDEX.HTM*
- Mystery of Smell: The vivid world of odors: *www.hhmi.org/senses/d110.html*
- Neuroscience for Kids: Brain songs: *http://faculty.washington.edu/~chudler/songs.html*
- Nondestructive Testing (NDT) Resource Center: Commercial applications of NDT: *www.ndt-ed.org/AboutNDT/aboutndt.htm*
- NOVA Online: Mystery of the senses (five-part series with naturalist Diane Ackerman): *www.pbs.org/wgbh/nova/teachers/programs/22s2_smell.html*
- Society for Neuroscience (SFN): Brain facts: A primer on the brain and nervous system: 74-page book, CD, and free pdf file: *www.sfn.org/index.aspx?pagename=brainfact*s
- Termites, Ink Pens and Pheromones: *www.learnnc.org/lessons/JackiClark5232002016*
- Termite Trails: *www.uky.edu/Ag/Entomology/ythfacts/resourc/tcherpln/termtrails.htm*

- Virginia Tech Physics Lecture Demo W20: Buzzer in a vacuum: *www.phys.vt.edu/~demo/demos/w20.html*
- Ward's Natural Science Co: Black Box Kits: #15 V 9878, 44 boxes and materials: $79.95: *www.wardsci.com/product.asp_Q_pn_E_IG0003323_A_Black+Box+Experiment*

Answers to Questions in Procedure, step #3

a. Most humans are used to relying heavily on their sense of sight. The restriction of not being able to open and look inside the canisters forces the learners to rely on their senses of hearing and touch to guess the identity of the canisters' contents.

b. Sound involves the vibration of matter via molecule-to-molecule collisions. Sound cannot travel through a vacuum, despite what students have seen in outer-space science fiction movies. This can be demonstrated live or via video clips (see Internet Connections: Virginia Tech).

c. Short of opening the canister, one cannot prove conclusively that the contents of two canisters are identical (and even then our sense of sight could be tricked). We can only say that in all the tests performed, the two canisters behaved identically. It is easier to determine that two canisters are different, as only one falsification test is needed. The logic of probable truths is important in both science and courts of law (the idea of "guilty beyond a reasonable doubt").

d. An operational model of a black box system that behaves in the same fashion as the unknown system lends confidence to the provisional truth of our informed guess. Scientists use mental, mathematical, computer simulation, and physical models to extend our knowledge.

e. Like stereoscopic vision, binaural hearing (that is, having two ears) enables organisms to assess the identity and relative location of a wide variety of environmental sounds and determine if the other organisms represent friend, foe, or food or are not immediately relevant. Hearing has an advantage over sight in that it works in the dark and around physical obstructions that limit seeing. Hearing impairment can result in psycho-social-emotional and cultural isolation, learning challenges, and safety risks. Research on improved hearing aids and prosthetic implants holds great promise.

f. As part of our higher cognitive functions, humans have developed language to communicate and cooperate with our peers. This use of language enables us to move beyond random trial and error and to share our own lessons learned with others. This ability is crucial to the evolution of science.

g. Black box systems are objects or processes that cannot be directly opened up and peered into to discover their inner structure and function. The history of science and technology is, in part, a story of the evolution of means of probing more deeply into previously hidden systems.

h. Ever-more-powerful sound, electromagnetic, and nuclear technologies and telescopes, microscopes, and medical diagnostic probes (e.g., CAT scans, MRIs, and PET scans) are enabling us to open up and look inside complex systems such as black holes, the nanoscale world of atoms and molecules, living human brains, and the human genome, often in nondestructive, noninvasive ways.

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