Challenging a Common Assumption of Hands-on Exhibits

How Counterintuitive Phenomena Can Undermine Inquiry

Joshua P. Gutwill

Abstract Some of the most intriguing science museum exhibits start with a counterintuitive outcome: a result that runs counter to visitors' expectations. Although counterintuitive events often succeed in captivating visitors, they rarely lead to visitor-driven inquiry. I argue that this is primarily due to two factors. First, for the counterintuitive effect to be presented reliably and repeatedly, the visitor's interaction must be limited to a narrow set of options. Without multiple options for visitors to explore, extended inquiry is nearly impossible. Second, counterintuitive outcomes beg the question "why did the outcome occur?". Answering such a "why" question through experimentation alone is too challenging for most visitors; they either leave the exhibit or turn to an explanatory label. In either case, the potential for inquiry is unrealized. Three strategies that both motivate visitor inquiry and allow for open-ended exhibit designs are presented: revealing beautiful aesthetics, supporting creativity, and providing engaging representations.

INQUIRY FROM COUNTERINTUITIVE OUTCOMES

At the heart of some of the most intriguing science museum exhibits are counterintuitive outcomes: results that run counter to visitors' expectations. More specific than surprise, a counterintuitive effect stimulates visitors' curiosity by challenging their previous understanding of the natural world. Take, for example, the San Francisco Exploratorium's exhibit *Water Standing*

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on Air. This exhibit invites visitors to turn over a column so that the water inside pours through a metal screen stretched across its center. If the column is rotated with just the right touch, much of the water will rest on top of the screen. Water will unexpectedly stand on air. Though it may seem like magic, the phenomenon is explained using the scientific concepts of surface tension and air pressure.[1] The effect is counterintuitive because it conflicts with the generally-held belief that unsupported objects fall down.[2]

For decades, science educators have used counterintuitive outcomes, originally called *discrepant events*, to motivate inquiry in classrooms.[3] The theory, based on the works of John Dewey and Jean Piaget, is that if students encounter a result that conflicts with their prior knowledge, they will want to resolve the contradiction.[4] In inquiry-based learning classrooms, teachers use this kind of conflict to motivate investigations in which students design and conduct experiments, make observations, analyze results, and draw conclusions.[5] Ideally, such an inquiry process leads to "accommodation," a restructuring of students' prior knowledge to fit with evidence presented by the counterintuitive event.[6] Conceptual change of this sort takes time; the initial counterintuitive event is merely the impetus for an extended learning experience.

In this paper, I argue that although such counterintuitive events have appealing educational qualities for schools, they actually inhibit the design of open-ended exhibits, thereby limiting inquiry opportunities for museum visitors.

COUNTERINTUITIVE OUTCOMES IN EXHIBITS

As with discrepant events in classrooms, exhibits with counterintuitive outcomes hook visitors and motivate them to learn more about the phenomenon. At *Water Standing on Air*, for example, visitors often become excited when they succeed in catching water on the screen, calling their friends over and wondering aloud why the water behaves in such an unexpected way. The power of counterintuitive outcomes to excite visitors undoubtedly accounts for their ubiquity in science museum exhibits. But rather than encourage visitors to pursue their questions through extended inquiry, exhibits like *Water Standing on Air* short-circuit the process by simply explaining the phenomenon in a label. Evaluation studies of this exhibit and others like it show that after reading the explanation, visitors find their curiosity has been satisfied and simply move on to the next exhibit. They do not engage in a more extended process of inquiry.[7]

A counter-intuitive outcome at the *Water Standing on Air* exhibit. *Photo courtesy of the Exploratorium.*

There are several problems with a learning process that begins with a surprising hook and prematurely ends with the museum's explanation. First, visitors are deprived of a potentially rewarding inquiry experience. According to learning scientist Daniel Edelson and his colleagues, inquiry in schools "provides students with the opportunity to achieve three interrelated learning objectives: the development of general inquiry abilities, the acquisition of specific investigation skills, and the understanding of science concepts and principles."[8] Similarly, in museums, asking questions and thinking of experiments to answer them helps visitors gain a deeper understanding of concepts, strengthen their decision-making abilities, and practice the skills of science.[9] Second, exhibits that do not afford inquiry may misrepresent what it means to do science.[10] Rather than stress the value of evidence-based experimentation for building, reorganizing, or applying knowledge,[11] didactic exhibits may convey the notion that scientific experimentation is nothing more than a simple sequence of "do, notice, and read."[12] Third, although an explanation leads visitors directly to the canonical science, it also communicates the museum's status as a scientific authority. Casting visitors in the role of mere recipients of information may leave them feeling slightly disempowered, less able to make sense of the world for themselves. Finally, an explanation serves as a convenient stopping point for the experience, subtly discouraging visitors from spending more time exploring the phenomenon.

In an effort to support inquiry, exhibit developers and visitor researchers in several museums around the United States have created and studied various types of open-ended exhibits that do offer ways for visitors to conduct their own experiments.[13] Not surprisingly, exhibits that present multiple options for visitor manipulation are more successful at supporting visitor-driven exploration than exhibits with few options.[14] However, exhibits with multiple options often overwhelm visitors with too many choices, making it difficult for them to understand the point of the exhibit.[15] One of the strengths of exhibits with a single counterintuitive outcome is that visitors are quickly engaged with the phenomenon and primed to learn more about it.

In the Exploratorium's *Active Prolonged Engagement* (APE) project, we attempted to obtain the best of both worlds by designing and studying exhibits that use counterintuitive outcomes to motivate visitors while also offering multiple options to support extended inquiry. This, we hoped, would more closely mirror the classroom method in which a discrepant event begins a prolonged inquiry process. To assess inquiry, we conducted formative evaluation and research studies with visitors, which involved measuring holding time, coding conversation, and observing physical interaction. Like design-based research,[16] our studies utilized the design process to develop general principles for fostering inquiry behavior. Full results of the studies are reported elsewhere.[17] In this article, I focus on the key design problem of pairing counterintuitive outcomes with multiple options for exploration, and I offer three design solutions that resulted from our work.

Open-ended Counterintuitive Exhibits

To create open-ended, counterintuitive exhibits, our developers turned to the research literature on misconceptions and perceptual illusions. One exhibit prototype we developed, called *Mystery Spot*, drew inspiration from a psychological study that investigated the illusions found at the Mystery Spot road-side attraction in Santa Cruz, California.[18] At the Mystery Spot, balls seem to roll uphill, people standing up straight appear to tilt sharply to one side, and pendulums swing asymmetrically. The rooms containing these amazing feats are noticeably rotated, but the secret to the illusion lies in the fact that the brain underestimates the angle of rotation. Hoping to utilize these counterintuitive illusions as motivators for visitor-driven investigations, we built our own room rotated to the angle specified in the literature. Although our exhibit successfully produced the fantastic illusions, the opportunities for investigation were limited. In the end, all questions led to a single answer: objects behave strangely because the room is rotated more than one thinks. Unfortunately, this conclusion is inaccessible to visitors, because they cannot measure the *perceived* angle of rotation for themselves. A formative evaluation study confirmed that while visitors were intrigued by the illusions, they did not investigate them.

Our developers worked on nearly a dozen counterintuitive exhibits. Many prototypes of such exhibits, including *Mystery Spot,* were abandoned because developers could not create open-ended designs.[19] Some exhibits of this type were completed for the project, but evaluation studies found that they were not effective at promoting inquiry activities.[20] Only one exhibit that began with a discrepant event successfully led to prolonged visitor engagement.[21] After years of trying to design exhibits in this mode, we concluded that it was a poor strategy. Our success in creating strong open-ended exhibits came only after we abandoned the belief that good exhibits start with a counterintuitive event.

Limitations of Counterintuitive Outcomes

Upon review, we found deeper reasons for the repeated failure of our prototypes:

First, counterintuitive outcomes require a specific setup to work properly. Open-ended exhibits often cannot be based upon counterintuitive outcomes because discrepant events work in only a narrow set of circumstances. In *Water Standing on Air*, for example, the exhibit was carefully designed to maximize the surprising result. The holes in the screen were made to be small enough to catch as much water as possible while still appearing large enough to amaze visitors. The water column was attached to a bearing so visitors would turn it over in just the right way. Both the holes and the column helped visitors suspend the maximum amount of water on the screen.

To see more clearly the incompatibility of counterintuitive outcomes with open-endedness, imagine trying to "open up" *Water Standing on Air* by adding more options for visitor manipulation. For instance, suppose the size of the holes were adjustable so visitors could test the effect of hole size on the water's behavior. Visitors would learn that larger holes can support less water while smaller holes can catch more water. Unfortunately, this humdrum result means that as the holes grow or shrink, the cognitive conflict disappears: it is not surprising that large holes cannot hold up much water, nor is it surprising that small holes can. The exhibit's original design lies at the peak of visitor surprise, and the cognitive conflict dissipates as the design is shifted down either side of that peak. The specific setup required for a counterintuitive outcome usually limits the number of options at an exhibit, thereby forcing the exhibit to be closed-ended.

Second, counterintuitive outcomes raise a "why" question in visitors' minds. When confronted with a counterintuitive result, people are eager to understand *why* it happened.[22] This strong desire to know "why" is the very reason discrepant events are used as motivators for inquiry. The problem for exhibits is that a "why" question is difficult to answer during a few minutes of physical exploration. Some form of mediation is usually required to guide visitors to the underlying science concepts. Rather than conduct experiments to answer their "why" questions, visitors simply look for an explanation from the museum.[23] Our evaluation studies bore this out: when we added explanations to the label at our *Downhill Race* exhibit, we found significantly *less* evidence of scientific thinking skills in visitors' conversations.[24] Although explanatory labels may satisfy visitors and even teach them science concepts, such labels may actually inhibit inquiry.

In summary, counterintuitive outcomes often restrict an exhibit's design to a specific arrangement and an explanatory label. Limiting visitors' options in this manner runs counter to the goal of promoting visitor-driven exploration and experimentation at exhibits.

SUCCESSFUL HOOKS FOR OPEN-ENDED EXHIBITS

Fortunately, there are other ways to hook visitors that are much more compatible with open-ended exhibit designs. At the Exploratorium, our research and evaluation studies have found that offering visitors beautiful aesthetics, opportunities for creation, and intriguing representations often leads to active prolonged engagement.[25] Rather than confounding visitors and defying their expectations, exhibits with these initial motivators delight visitors and invite them into a mode of playful exploration.

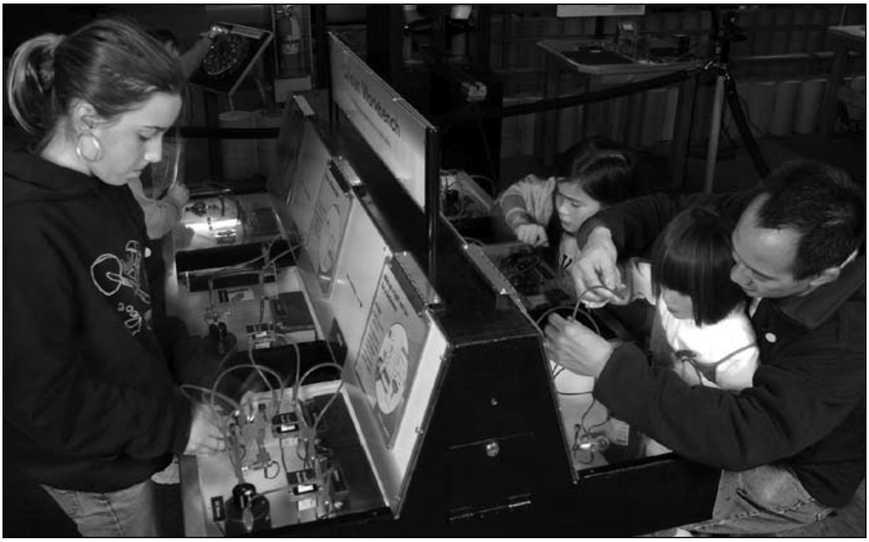
Visitors encounter crystalline structures at Watch Water Freeze. *Photo courtesy of Lily Rodriguez, Exploratorium.*

Revealing Beautiful Aesthetics

Visitors will spend time carefully observing a beautiful phenomenon, such as the colorful water crystals at the exhibit entitled *Watch Water Freeze*. Using polarizing filters, the exhibit presents the familiar material of ice as a beautiful interactive painting, full of vibrant crystalline structures that visitors can explore by melting and freezing the ice. Visitors become engaged in changing the structures and colors of the ice, practicing the inquiry skills of observation and experimentation along the way. Beauty can be just as engaging as a counterintuitive result but does not require a narrow set of parameters to achieve. At *Watch Water Freeze*, melting the crystals and freezing the water both lead to strikingly colorful, feathered formations.

Offering Opportunities for Creation

Construction activities can also engage visitors in prolonged inquiry. This includes having visitors build their own artifacts. For example, at *Circuit Workbench,* visitors connect banana cords—flexible, interconnecting wires with plugs on each end—to power a collection of everyday electrical components. Visitors delight in making a light bulb turn on, a motor spin, or a bell ring. After successfully creating a simple circuit, visitors often build more complex circuits involving multiple components in series or in parallel. The creative process engages visitors' skills at experimentation and design as they work within the parameters of the tools provided.



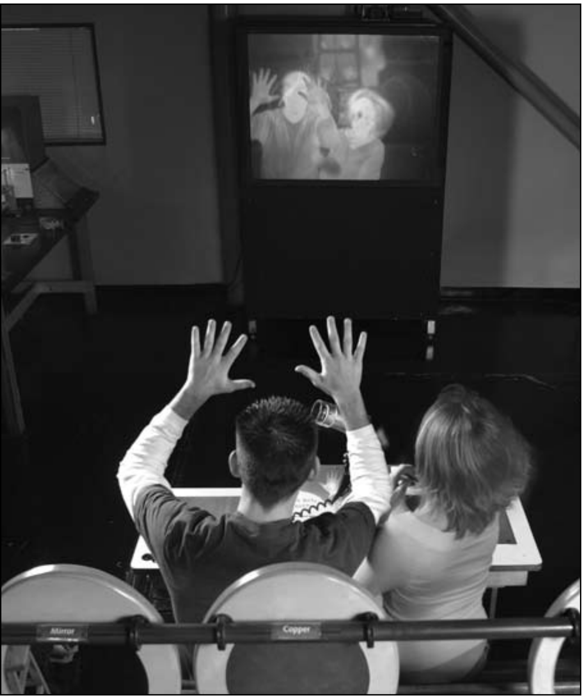
Building circuits at *Circuit Workbench. Photo courtesy of Lily Rodriguez, Exploratorium.*

Presenting Intriguing Representations

Finally, exhibits that offer interesting representations of phenomena can also inspire extended exploration. For example, *What's Hot, What's Not?* invites visitors to see themselves in new ways by representing their body heat as a grayscale video image. While looking intently at their heat images, visitors perform a wide range of physical activities to change or reveal the heat from their bodies. They open and close their mouths, rub their hands together or on their bodies, compare temperatures of their body parts, and use a blow dryer and even nearby exhibits to heat and cool themselves. Along the way, visitors build a mapping from the grayscale representations to the heat of their body parts. In short, they practice the inquiry skills of observing, experimenting, comparing, transforming, and inferring. Intriguing representations seem to motivate visitors just as well as a counterintuitive outcome, but they also lead to prolonged engagement through open-ended exhibit design.

DISCUSSION

Counterintuitive events act as powerful motivators for extended inquiry in science classrooms. However, simply importing this part of the inquiry process into museums can actually inhibit the design of successful inquiry



Visitors explore an intriguing representation of themselves at *What's Hot? What Not?. Photo courtesy of Lily Rodriguez, Exploratorium.*

experiences.[26] As we have seen, counterintuitive outcomes often lead to a closed-ended sequence of "do, notice, and read" at science museum exhibits.[27] In the APE project, we found it extremely difficult to engineer both a surprising result and multiple options for exploring that result in a single exhibit. All too often, our attempts either ended in failure or produced closed-ended exhibits. I have argued that this failure to promote inquiry stems in part from the requirement that the exhibit be designed in a specific manner to maximize the counterintuitive effect. If the objective is to build open-ended exhibits, developers' time is best spent looking for different ways to motivate engagement.

Creating open-ended exhibits that support visitor-driven inquiry is a worthwhile goal for science museums. At such exhibits, visitors may learn and practice the skills of science, exercise their decision-making capacities, and feel empowered to make sense of the natural world. Open-ended designs can shift visitors' experience in the museum from what George Hein and others in the learning sciences call "discovery" learning to "constructivist" or "inquiry" learning.[28] In a discovery mode, learners actively create new knowledge, but must come to conclusions determined by others. The point of a discovery exhibit is to bring museum visitors to a canonically correct scientific idea. According to Hein, constructivist learning also posits that visitors actively build knowledge, but the understanding they create is not validated by whether it conforms to an external standard of truth. Rather, the validity of a learner's conclusion comes from its relationship to prior knowledge and its usefulness for further experimentation.[29]

The open-ended exhibits created in the APE project foster constructivist learning of the sort described by Hein and by learning scientists. Rather than try to uncover a previously determined scientific fact, museum visitors investigate the world for themselves by exploring beautiful ice crystals at *Watch Water Freeze*, building exciting circuitry at *Circuit Workbench*, or experimenting with heat images at *What's Hot, What's Not?* If our goal is to create a constructivist museum, designing exhibits that combine delightful hooks with multiple options is an effective way to achieve it.

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Notes

1. Surface tension in the water covering the screen prevents air from moving through the screen, trapping the air in the two halves of the column. Simultaneously, a little of the water presses down through the holes, compressing the air below and rarefying the air above. This pressure difference in the air holds up the water.
2. Andrea diSessa, "Toward an Epistemology of Physics," *Cognition and Instruction* 10, no. 2-3 (1993): 105-225.
3. For example, see J. Richard Suchman, *The Elementary School Training Program in Scientific Inquiry*. (Urbana, IL: University of Illinois, 1962); Alfred E. Friedl, *Teaching Science to Children: The Inquiry Approach Applied* (New York: Random House, 1972); Tik L. Liem, *Invitations to Science Inquiry*. Second ed. (Lexington, MA: Ginn Press, 1987); Emmett Wright and Girish Govindarajan, "Discrepant Event Demonstrations," *The Science Teacher* 62, no. 1 (1995): 24-28.
4. John Dewey, *How We Think* (New York: D.C. Heath & Co., 1910); Jean Piaget and Barbel Inhelder, *The Psychology of the Child*, translated by Helen Weaver. (New York: Basic Books, 1969).

5. Daniel C. Edelson, Douglas N. Gordin, and Roy D. Pea, "Addressing the Challenges of Inquiry-Based Learning Through Technology and Curriculum Design." *Journal of the Learning Sciences* 8, 3 (1999): 391 – 450; Barbara White, "Thinkertools: Causal Models, Conceptual Change, and Science Education," *Cognition and Instruction* 10, no. 1 (1993): 1-100; Barbara White and John Frederiksen, "Inquiry, Modeling and Metacognition: Making Science Accessible to All Students," *Cognition and Instruction* 16, no. 1 (1998): 3-118.
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7. Carey Tisdal and Deborah Perry, "Going Ape at the Exploratorium: Interim Summative Evaluation Report." 67. (Chicago: Selinda Research Associates, 2003).
8. Edelson, Gordin, and Pea, "Inquiry-Based Learning," p 393.
9. Hubert Dyasi, "What Children Gain by Learning through Inquiry," In *Inquiry: Thoughts, Views and Strategies for the K-5 Classroom*, ed. Lynn Rankin, 120. (Arlington: National Science Foundation, 1999), 9-13.
10. Clark A. Chinn and Betina A. Malhotra, "Epistemologically Authentic Inquiry in Schools: A Theoretical Framework for Evaluating Inquiry Tasks." *Science Education* 86, no. 2 (2002): 175-218.
11. Edelson, Gordin, and Pea, "Inquiry-Based Learning."
12. Tisdal and Perry. "Going Ape at the Exploratorium."
13. Examples include the *Experiment Benches* exhibition at the Science Museum of Minnesota; the *Investigate!* exhibition at the Museum of Science, Boston; the PISEC study by Minda Borun and colleagues and the *Active Prolonged Engagement* (APE) exhibition and study at the Exploratorium.
14. Minda J. Borun, J. I. Dritsas, N. E. Johnson, K. F. Peter, K. Fadigan, A. Jangaard, E. Stroup, and A. Wenger. "Family Learning in Museums: The PISEC Perspective." Association of Science-Technology Centers, 1998; Gutwill, Joshua P. "Observing Ape." In *Fostering Active Prolonged Engagement: The Art of Creating Ape Exhibits*, ed. Thomas Humphrey and Joshua Gutwill. (San Francisco: Exploratorium, 2005), 5-22.
15. Sue Allen and Joshua Gutwill. "Designing with Multiple Interactives: Five Common Pitfalls," *Curator* 47, no. 2 (2004): 199-212.
16. Ann Brown, "Design Experiments: Theoretical and Methodological Challenges in Creating Complex Interventions in Classroom Settings." *Journal of the Learning Sciences* 2, no. 2 (1992): 141-78; Paul Cobb, Jere Confrey, Andrea diSessa, Richard Lehrer, and Leona Schauble, "Design Experiments in Educational Research," *Educational Researcher* 32, no. 1 (2003): 9-13; Daniel C. Edelson, "Commentary: Design Research: What We Learn When We Engage in Design," *Journal of the Learning Sciences* 11, no. 1 (2002): 105 - 21.
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18. Arthur Shimamura and William Prinzmetal, "The Mystery Spot Illusion and Its Relation to Other Visual Illusions," *Psychological Science* 10, no. 6 (1999): 501-07.
19. For details about these "abandoned" exhibits, see the APE website at: http://www.exploratorium.edu/partner/ape/ape_exhibits_abandoned.html.
20. S. Buennagel and J. Gutwill, "Avalanche," http://www.exploratorium.edu/partner/pdf/Avalanche_v2_vdrp_06.pdf; J. Gutwill, "Rotating Mirrors," http://www.exploratorium.edu/partner/pdf/Rotng_Mirs_vdrp_V1_03.pdf.
21. J. Gutwill, "Downhill Race: A formative evaluation study comparing three types of rolling disks" http://www.exploratorium.edu/partner/pdf/Downhill%20Race_V2-4_rp_04.pdf
22. Friedl. *Teaching Science.*
23. George Hein (Professor Emeritus, Lesley College), in discussion with the author, December 2007; Tisdal and Perry. "Going Ape at the Exploratorium."
24. J. Gutwill, "Downhill Race," http://www.exploratorium.edu/partner/pdf/Downhill%20Race_V2vsV3_rp_07.pdf.

25. Humphrey and Gutwill, *Active Prolonged Engagement*.
26. For more on the challenges of context in designing inquiry-based learning experiences, see Edelson, Gordin, and Pea, "Inquiry-Based Learning," p. 400.
27. Tisdal and Perry. "Going Ape at the Exploratorium," p. 67.
28. George E. Hein, *Learning in the Museum*, (New York: Routledge, 1998); Edelson, Gordin, and Pea, "Inquiry-Based Learning."
29. Hein, *Learning*, 34.

Joshua P. Gutwill is acting Director of Visitor Research and Evaluation at the Exploratorium, the museum of science, art and human perception in San Francisco. His exhibit research and development interests include creating opportunities for visitors to engage in self-directed inquiry in science museum settings.