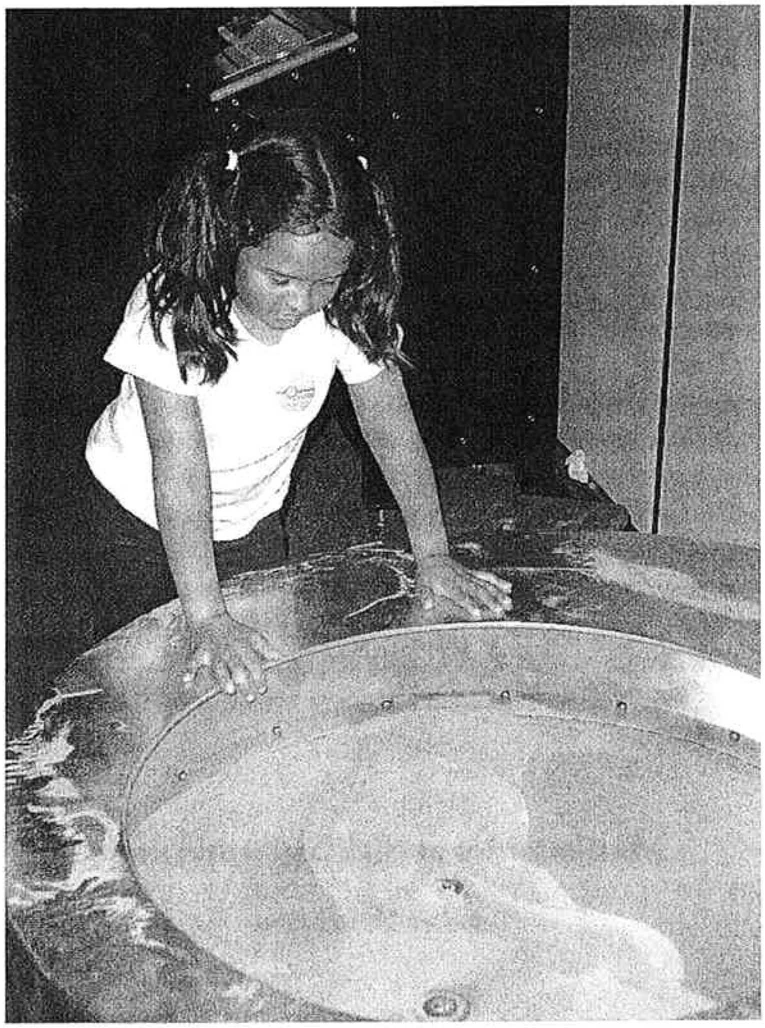

The Exploratorium
www.exploratorium.edu

The Exploratorium

An Inquiry into Including Mathematics

The Exploratorium, in San Francisco, California, is not a typical case study for seeing what a science center has done in mathematics. Rather it illustrates how one science center, steeped in a "culture of inquiry," conceives ways to amplify or launch a mathematics presence. The questions the Exploratorium staff pursues, with regard to mathematics, are many of the same questions that the site-visit teams entertained throughout their visits. For example, the Exploratorium staff is considering how to make explicit the mathematics inherent in science exhibits.

Exhibit-based learning and personal inquiry—the legacy of Frank Oppenheimer—hold firm in the Exploratorium's self-definition and practice. Exhibits invite visitors "to do and notice" and education programs engage teachers in inquiry. The atmosphere of inquiry influences staff to imagine new approaches, ask "what if," and take risks in trying out ideas. The current work in mathematics is a work in progress—an inquiry—in which staff asks questions about best approaches, about using technology in new ways, and about planning for the future.

At the Exploratorium we found mathematics included in teacher workshops, publications, on the award-winning web site, and within exhibits. This case study describes how the Exploratorium has developed each component.

Mathematics at the Exploratorium

Teacher Education

The Teacher Institute

The Exploratorium launched the Teacher Institute for secondary-school physical science, open to teachers of science or mathematics in grades 6 to 12, during the 1980s. In part, the Institute was conceived as a way to draw teachers into the science center. By working with, and learning from the exhibits, teachers were more likely to bring their classes during the academic year. The National Science Foundation recognized the Teacher Institute as a credible professional development experience for science teachers and provided several years of ongoing funding. NSF continues to fund the Teacher Institute, which now also receives support from the State of California, Eisenhower, and foundations such as Hewlett and Noyce.

Mathematics first surfaced in the Teacher Institute when Thomas Humphrey, Exploratorium senior scientist, wondered about making the underlying mathematics in the physics exhibits more overt and explicit for teachers. Lori Lambertson, a teacher from a local district, joined the staff and began collaborating with Humphrey to explore the idea. They started by looking at existing exhibits with a mathematics lens and finding objects from which mathematical concepts could be discovered. They explained to teachers that *rather than focusing on the scientific principle in an exhibit, their task is to use the phenomena as a way to understand mathematics.*

This approach, according to Dennis Bartels, former Director of Teaching and Learning at the Exploratorium,

may be the easiest and most productive way for science centers to connect with mathematics. Applying a mathematics filter to existing exhibits and making the interpretation of the mathematics accessible to the visitor is relatively simple and cost-effective. New exhibits do not need to be constructed in order to do mathematics in the museum.

The Teacher Institute experiment with mathematics was captured in a video sequence called "Making a Difference," produced by PBS as part of its 1998 series *Life by the Numbers.* The video makes the point that science centers express a key principle of mathematics reform: relating mathematics to real-world examples. In a segment likely to connect with science center professionals, narrator Danny Glover makes an analogy between learning mathematics and learning a building trade. He notes that too frequently studying mathematics is like listening to lectures about hammers, screwdrivers, and the like:

At the end of the course you might know a lot about the tools, but still have no idea how to use them. This is how we have been teaching mathematics. Students memorize symbols and formulas, but they aren't taught the concepts that lie at the heart of mathematics. In short we have been teaching them tools, but not how to use them.

A real-world connection and authentic use of mathematical tools are core to the approach offered by the Teacher Institute. The teachers investigate real-world phenomena, and the process is reflective of the same intellectual engagement mathematicians and scientists employ. For the teachers, the real science phenomena, the mathematics, and the insights about teaching and learning make the Teacher Institute a powerful experience.

While teachers sometimes struggle with their own learning, they always reflect on how to translate these experiences into classroom lessons. To support them, the staff conducts Saturday workshops during the academic year to augment the experiences of the four-week Summer Institute. The teachers' conceptual understanding is improved, and the participants benefit from sharing classroom applications.

Over the course of 16 years, the Exploratorium has managed a fine balance between sustaining the popular Teacher Institute program and initiating new approaches (within the existing structure) that are attractive to funders. For example, the Teacher Institute now separates the physics and mathematics learning experiences into two summer sessions. The one for mathematics teachers is called "*Where's the Math*?"

Other changes have come in consequence of the decline in the number of qualified science and mathematics teachers staying in teaching. Turnover and decisions to leave teaching within the first three years of a career have serious ramifications for schools needing qualified staff. The Exploratorium has now modified the Teacher Institute to serve "new" science teachers—those in their first or second year of teaching—and involve alumni from prior institutes as mentors. Although the Exploratorium has launched this approach only in science education, it seems it could translate to mathematics professional development quite easily.

Mathematics on the Exploratorium web site

The Exploratorium created its award-winning web site[12] virtually at the birth of the World Wide Web. The fact that the Exploratorium has had a web presence since 1994 bespeaks institution support and strong leadership in this area. The web site is very comprehensive and has enormous potential to support mathematics in science centers. Since there are many directions one can go from the opening home page, it is advisable for readers to explore on their own. The following web site components were selected for this report because of their mathematics connections.

Snacks

Recasting Exploratorium experiences into student-centered, classroom-based lessons resulted in one of the Exploratorium's most teacher-friendly products, the Exploratorium *Science Snackbook.* This remarkable publication of teacher-created, small-scale exhibits for the classroom, known to staff as the *Snacks,* was the by-product of early Teacher Institutes. According to staff,

> *the* Snacks, *while not the "full-meal deal" of a science center visit, gives students a flavor of the informal learning experience.*

The *Snackbook* continued to evolve, included mathematics activities, and with the advent of the web site, the *Snacks* inevitably became a "cyber buffet" for teachers across the country who require their students to read and do activities from the *Exploratorium Snacks* page. Shown in Table 2 are modified versions[13] of activities from the *Math Snacks* page, with their corresponding NCTM Standards.

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[12] In 2000 the Exploratorium's web team earned ASTC's second annual Award for Innovation for their online achievement in developing www.exploratorium.edu.
[13] All images from the Exploratorium web site are proprietary. The science center's willingness to share and permit these images to be presented in modified format is appreciated.

Table 2. Activities on the Exploratorium's Math Snacks web page

SNACKS EXPLORATORIUM SNACKS

Snack Name	Description	NCTM Standards
Corner Reflector	The observer studies reflections in two mirrors set at right angles.	• Standard 3 – Geometry and Spatial Sense (items 3.1 and 3.4) • Standard 4 – Measurement (item 4.2) • Standard 7 – Reasoning and Proof (item 7.2) • Standard 9 – Connections (items 9.1 and 9.3)
Inverse Square Law	Explore why the world gets dark so fast outside the circle of the campfire.	• Standard 1 – Numbers and Operations (items 1.1 and 1.2) • Standard 2 – Patterns and Functions (item 2.1) Standard 3 – Geometry and Spatial Sense (item 3.1) Standard 4 – Measurement (item 4.2) Standard 5 – Data Analysis and Statistics (item 5.1) Standard 6 – Problem Solving (item 6.1) Standard 7 – Reasoning and Proof (item 7.2) Standard 8 – Communication (item 8.1) Standard 9 – Connections (items 9.1 and 9.3)
Radioactive Decay Mode	Use coins to create a model for radiation	• Standard 1 – Numbers and Operations (item 1.1) • Standard 2 – Patterns and Functions (items 2.1, 2.2, and 2.3) • Standard 3 – Geometry and Spatial Sense (item 3.1) • Standard 4 – Measurement (item 4.2) • Standard 6 – Problem Solving (item 6.1) • • Standard 9 – Connections (item 9.1) • Standard 10 – Representation (item 10.3)
Solar Brightness	A photometer made by making grease spots on white paper can be used to compare the brightness of the sun to the brightness of a lamp. By finding a position at	• Standard 1 – Numbers and Operations (item 1.1) • Standard 2 – Patterns, Functions, and Algebra (items 2.1 and 2.2) • Standard 3 – Geometry and Spatial Sense (item 3.1) • Standard 4 – Measurement (item 4.2)

	which the sun is as bright as the lamp, the power output of the sun can be estimated.	• Standard 6 – Problem Solving (item 6.1) • Standard 9 – Connections (items 9.1, 9.2, and 9.3) • Standard 10 – Representation (item 10.3)
Spinning Blackboard	Create graceful loops and spirals by drawing on a spinning dish.	• Standard 2 – Patterns, Functions, and Algebra (item 2.1) • Standard 3 – Geometry and Spatial Sense (items 3.1 and 3.3) • Standard 5 – Data Analysis and Statistics (item 5.1) • Standard 6 – Problem Solving (item 6.1) • Standard 9 – Connections (item 9.3) • Standard 10 – Representation (item 10.3)
Spinning Cylinder	A spinning rod with a mark near one end is set rotating and spinning at the same time. Amidst the blur of the spinning cylinder, the mark appears three times, forming a stationary triangle.	• Standard 1 – Numbers and Operations (item 1.2) • Standard 2 – Patterns, Functions, and Algebra (items 2.1 and 2.2) • Standard 4 – Measurement (items 4.1 and 4.2) • Standard 5 – Data Analysis and Statistics (item 5.1) • Standard 6 – Problem Solving (item 6.2) • Standard 9 – Connections (items 9.1, 9.2, and 9.3) • Standard 10 – Representation (item 10.3)
Strange Attractor	The attraction and repulsion of magnets produces entrancing, unpredictable motion.	• Standard 2 – Patterns, Functions, and Algebra (item 2.1) • Standard 5 – Data Analysis and Statistics (item 5.1) • Standard 6 – Problem Solving (item 6.3) • Standard 9 – Connections (item 9.3)
Take It from the Top	Wooden blocks, stacked so the top block extends completely past the end of the bottom block, seem to defy gravity. A pattern emerges for how to place each block.	• Standard 2 – Patterns, Functions, and Algebra (items 2.1, 2.2 and 2.3) • Standard 5 – Data Analysis and Statistics (item 5.1)
Tired Weight	This Snack activity shows middle school and older students how to calculate the weight	• Standard 2 – Patterns, Functions, and Algebra (item 2.2) • Standard 4 – Measurement (items 4.1 and 4.2)

	of a car by finding the surface area of a tire footprint. It reinforces the understanding of surface area and units used in the measurement of area and pressure. It also provides an example of dimensional analysis, where measurements units are treated as parts of an equation.	• Standard 5 – Data Analysis and Statistics (item 5.1) • Standard 6 – Problem Solving (item 6.3) • Standard 9 – Connections (items 9.1, 9.2, and 9.3) • Standard 10 – Representation (item 10.3)
Vector Toys	Components of force cause this robot toy to walk and stop at just the right time.	• Standard 1 – Numbers and Operations (items 1.1, 1.2, and 1.3) • Standard 2 – Patterns, Functions, and Algebra (item 2.2) • Standard 3 – Geometry and Spatial Sense (items 3.1 and 3.2) • Standard 4 – Measurement (items 4.1 and 4.2) • Standard 5 – Data Analysis and Statistics (item 5.1) • Standard 6 – Problem Solving (item 6.2) • Standard 9 – Connections (items 9.1, 9.2, and 9.3) • Standard 10 – Representation (item 10.3)

Other web site links to mathematics

The Exploratorium has linked other mathematics web sites to its own web site. A few of the mathematics sites are listed below. Check out the Exploratorium's Cool Sites web page for the rest.

Table 3. Exploratorium web site links to mathematics

Exploremath.com	http://www.exploremath.com/
Cool Math 4 Kids	http://www.coolmath4kids.com/
Figure This! Math Challenges for Families	http://www.figurethis.org/index40.htm
The Abacus: The Art of Calculating with Beads	http://www.ee.ryerson.ca:8080/%7Eelf/abacus/
Native American Geometry	http://www.earthmeasure.com/
The Math Forum	http://forum.swarthmore.edu/
The KnotPlot Site	http://www.cut-the-knot.com/content.html
Julia and Mandelbrot Set Explorer	http://aleph0.clarku.edu/~djoyce/julia/explorer.html

Science Explorer

Another section of the Exploratorium web site that addresses mathematics is the *Science Explorer,* based on the Exploratorium's award-winning publication of the same name.

In the example below, "Geodesic Gumdrops" (extracted and modified from the web site), students explore geometric shapes with simple materials and learn about the properties of squares and triangles. The corresponding NCTM Standards are:

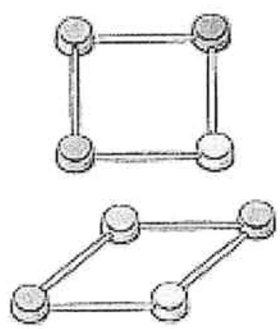
- Standard 3 – Geometry and Spatial Sense (item 3.1)
- Standard 5 – Data Analysis, Statistics and Probability (item 5.1)
- Standard 6 – Problem Solving, (item 6.1)
- Standard 9 – Connections (item 9.3).

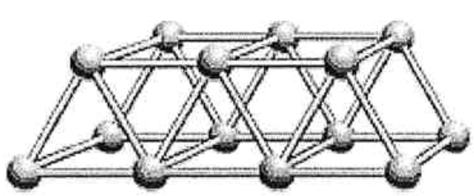
Geodesic Gumdrops

Make amazing architecture with candy and toothpicks.

What's Going On?	What's the big deal about triangles?

As you've probably already discovered, squares collapse easily under compression. Four toothpicks joined in a square tend to collapse by giving way at their joints, their weakest points. A square can fold into a diamond, like this:



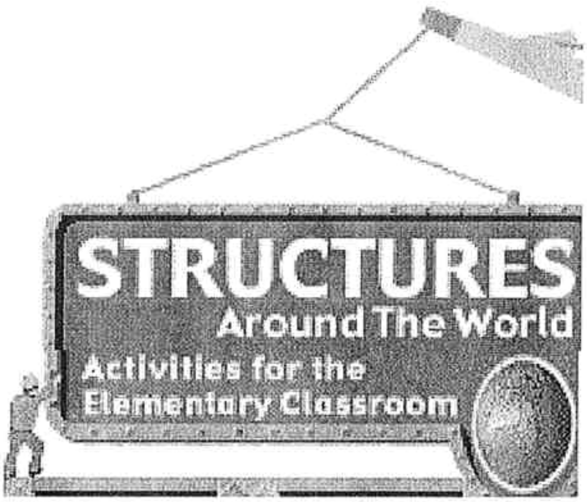


But if you make a toothpick triangle, the situation changes. The only way to change the angles of the triangle is by shortening one of the sides. So to make the triangle collapse you would have to push hard enough to break one of the toothpicks.

Mathematics Publications

Scale and Structures

The Exploratorium has published a number of books that have a mathematics orientation. *Scale and Structures,* available through the Exploratoriumweb site, www.exploratorium.edu, introduces elementary students and teachers to a number of measurement and geometry concepts. The image below is modified from the Exploratorium web pages.



Straws and Pins
Garden Poles

Cylinders and Scale
Clay Beams and Columns
Skewers and Garden Poles

Clay Bridges
Paper Bridges
Newspaper Bridges

Math Explorer

The newest Exploratorium mathematics publication is *Math Explorer*. Recognizing that middle school mathematics was a failing point for U.S. teenagers, the staff undertook a project to publish math activities intended for use with out-of-school youth development programs. NSF funded development of this project, and it is currently in the trial-testing phase.

Fifteen youth development programs, in California and other states, are testing 12 different activities each, from a total of 35, and providing feedback to staff about their usefulness and effectiveness with children. The programs also provide information about activities that they do not use and give the reasons why. Although most activities have met with approval, the staff has discovered that issues like reading level affect success. In a slightly modified format, *Math Explorer* is being tested by families for home use.

Lori Lambertson, the Exploratorium's project activity developer, has built-in components to make the book useful and friendly. Activities are charted with the corresponding California and

NCTM Standards and organized by skills or practices introduced. This latter component may prove most attractive to the community-based groups and families.

Interestingly, many potential consumers of mathematics are looking to remediate students on what they perceive to be the core mathematics skills. Although mathematics enthusiasts may find this step dismaying, the Exploratorium is creating a bridge by designing activities that excite learners and "sneak" in the skills practice. Additional information about *Math Explorer* can be found at http://www.exploratorium.edu/math-explorer.

Mathematics Exhibits

Many Exploratorium floor exhibits engage visitors in exploring light, sound, and perception. In the center of the hall, on the mezzanine, are a number of exhibits intentionally designed for mathematics exploration. This is a relatively small area in comparison with the overall layout. It was developed in the early 1980s, with funds from the Ford Foundation.

Of course, mathematics can be found in other Exploratorium exhibits as well. The challenge is in helping the visitor to know what mathematics is being presented. This is a significant question that Exploratorium staff are pondering. The mathematics is obvious to visitors who have a strong conceptual understanding of the discipline. However, most Exploratorium visitors are attracted by the phenomena and the investigative play that exhibits offer. Often they are unmindful of the underlying mathematics. To help bring out the mathematics content, the Exploratorium is considering a variety of approaches, including the use of hand-held computer technology.

Table 4 names and describes some of the exhibits that address mathematics. As you will see, most of the mathematics in the exhibits appears to be appropriate for middle school and high school levels.

Table 4. Mathematics Exhibits at the Exploratorium

Exhibit	Description	NCTM Standards	Grade Level
Gravity's Rainbow	Several balls, spaced unevenly, roll down an adjustable ramp; the visitor tries to land them in evenly spaced cups.	Standard 2 – Patterns, Functions, and Algebra (items 2.1 and 2.3) Standard 3 – Geometry and Spatial Sense (items 3.1 and 3.4) Standard 5 – Data Analysis and Statistics (items 5.1 and 5.3) Standard 6 – Problem Solving (items 6.3 and 6.4) Standard 9 – Connections (item 9.3)	7–11
Make Bubbles	Create soap bubbles of various shapes.	• Standard 3 – Geometry and Spatial Sense (items 3.1, 3.3,. and 3.4) • Standard 9 – Connections (items 9.1 and 9.3)	10–12
Radioactive Decay Model	Use cubes to represent the decay of elements over time.	• Standard 2 Patterns, Functions, and Algebra (items 2.1, 2.2, and 2.3) • Standard 5 – Data Analysis Statistics, and Probability (items 5.1, 5.2, and 5.3) • Standard 9 – Connections (items 9.1 and 9.3)	9–12
Lens Table	On an optical bench, visitors construct lens arrangements that enlarge or reduce an image.	• Standard 3 – Geometry and Spatial Sense (items 3.1, 3.3, and 3.3) • Standard 5 – Data Analysis Statistics, and Probability (items 5.1) • Standard 6 – Problem Solving (item 6.1) • Standard 9 – Connections (items 9.1, 9.2, and 9.3)	10–12

Exhibit	Description	Standard	Grade Level
Big Wheel	Making various patterns on a revolving cylinder creates music. Different patterns play different notes.	• Standard 2 – Patterns, Functions, and Algebra (item 2.1) • Standard 3 – Geometry and Spatial Sense (items 3.1 and 3.3) • Standard 6 – Problem Solving (item 6.1) • Standard 9 – Connections (items 9.1 and 9.3)	K–12
Big Chair, Little Chair	This exhibit allows the visitor to develop an understanding of what it means to double dimensions. All ages can study how much bigger the double-sized chair appears to be. Older children and adults can explore what happens to the surface area of the chair when the dimensions are doubled. Likewise, they can explore what happens to the volume of the seating space when dimensions are doubled. A guided discussion can help visitors explore the difference between doubling only one dimension of a *square,* versus doubling both dimensions. Also what happens when doubling only one or two dimensions of a *cube,* versus doubling all three dimensions.	• Standard 3 – Geometry and Spatial Sense (items 3.1 and 3.4) • Standard 4 – Measurement (item 4.2)	6–9
Singing Coach	Try to match the pitch.	• Standard 2 – Patterns, Functions, and Algebra (item 2.1) • Standard 9 – Connections (items 9.1 and 9.3)	7–10

Partnerships

To achieve success with its various programs for mathematics teachers, the Exploratorium has developed relationships with local school districts and two nearby universities. The science center has an informal relationship with the University of San Francisco to support preservice teachers in learning. A more formal relationship exists with San Francisco State University, which allows credit to be given for workshops. The Exploratorium also has a program called Teachers in Residence, whereby teachers can spend a year working at the Exploratorium. It is this program that first brought mathematics educators into the science center.

Evaluation

Like most science centers working with mathematics, the Exploratorium has done almost no research on the effectiveness of programs or products. There are anecdotes—and the *Snacks* web pages permit teachers to chat with one another. There is data collection and feedback about how consumers use and respond to products, such as the trial testing of the *Math Explorer* book. But systematic collection of data, of the kind that would satisfy certain funders, is missing.

Lessons Learned

The "tyranny of the blackboard" can prevent mathematics teachers from using a hands-on approach.

According to Exploratorium staff:

> *[In teaching mathematics] there exists a strong tradition of using the blackboard, writing equations...and drawing graphs.*

For many teachers of mathematics, this tradition is hard to change. Some of the Teacher Institute participants were so wedded to the blackboard tradition that they felt they could never teach in the manner exemplified by the Exploratorium staff. For this group of teachers, stepping away from getting exact answers was too difficult. They want to find the "right" answer.

Unfortunately, real-world numbers obtained through investigations of the natural world (and with science center exhibits) may not always "fit." Sometimes data that are "good enough" have to be accepted. The process of trying to understand the stuff of the real world rather than "knowing the answers" can be disconcerting if one needs or expects precision.

For other teachers, mathematics concepts gained by studying phenomena were "cool." These teachers were able to see mathematics as a language to represent or convey natural, noticeable patterns in the world. They are the ones who clamor for seats at the half-day Saturday workshops the Exploratorium offers during the academic year.

The Saturday workshop experiences prepare the teachers in important ways. For example, in addition to gaining deeper understanding of mathematics concepts, they learn the kinds of challenges their own students have when trying to solve problems. Anticipating problems reduces student frustration and increases learning when experiments or activities are replicated in the classroom.

Shifting teacher learning experiences to more engaging and authentic use of mathematics may help defeat the notion that "teachers teach as they are taught." However, the tenacity of the image[14]—and reality—of teachers standing in front of the classroom, reviewing homework and showing how to use algorithms, is powerful (*Eighth-Grade Mathematics Lessons: United States, Japan, and Germany*, 1997). Certainly, it will take more than an Exploratorium "*Where's the Math?*" Teacher Institute to make changes in teacher behavior, but the science center's approach offers an alternative image for teachers to consider.

Many exhibits have "hidden mathematics," which need some form of interpretation for the visitor.

For many of the exhibits within the Exploratorium (and other science centers) there is an underpinning of mathematics. But the mathematics implicit in the phenomenon is usually not noticeable to the casual visitor without interpretation. Sometimes the visitor lacks the conceptual knowledge of the mathematics, but often the exhibit phenomenon simply doesn't elicit the mathematics the visitor *does* know. For the most part, visitors do not see through the lens of mathematics in viewing exhibits and consequently miss the connection.

This conundrum stimulated an ongoing question for the site-visit teams and staff at all of the science centers visited: Does mathematics reside in the exhibit or in the person? The perspective one takes on this question influences decisions such as determining copy on labels and deciding whether staff should "interpret" the mathematics or whether there are alternative strategies, perhaps untried, for elevating mathematics awareness.

The Exploratorium is considering a strategy of using hand-held computer devices that would enable the visitor to "play" with exhibits in novel ways. The Palm, or pocket, computer might also be programmed to include more extensive and detailed information about the exhibit.

Staff time for personal reflection and experimentation is an effective R & D strategy.

The Exploratorium recognizes that to do and present inquiry successfully, staff needs time to think. According to staff members, time for reflection and personal experimentation with exhibits, activities, and ideas is part of the Exploratorium's research and development strategy. The site-visit team was impressed with the freedom, opportunity, and encouragement given staff to try new approaches and to address new areas. We wondered if there was a correlation between the R & D approach and the number of grant-funded projects that the Exploratorium receives.

[14] This image mirrors the teaching efforts of the U.S. 8th grade mathematics teachers captured on the TIMSS video.

Investment in human resources reduces staff turnover and increases the institutional capacity to develop and deliver programs and exhibitions.

The site-visit team noted that both of the Bay Area science centers reviewed (the Exploratorium and the Lawrence Hall of Science) had high-caliber staff who earned significant salaries and had long careers with the science center. For the site-visit team, and indeed during later site visits, the discussions centered on the implications of constantly needing to train new people as a consequence of high turnover. Investment in human resources seems to result in low staff turnover and appears to reap the rewards of increased capacity to develop fundable projects, cultivate sustainable partnerships and secure grants.

To do mathematics in a science center, the institution must have access to mathematicians and/or mathematics educators. These can be individuals on an advisory board or part-timers working on special projects. But sustaining successful mathematics in an institution where science is king means sustaining a person on staff who is enthusiastic about mathematics content. High staff turnover threatens the potential for success.