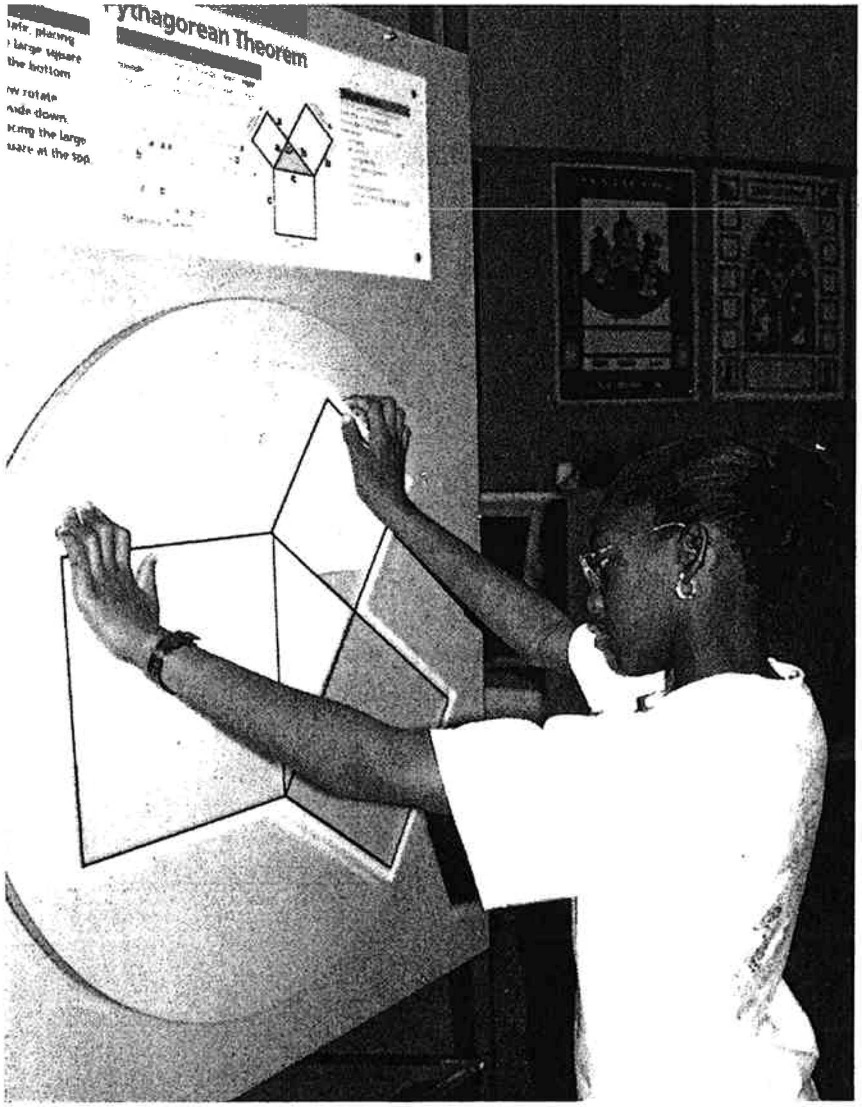


Findings, Emerging Issues, and Recommendations

Findings

The findings grow out of the lessons learned from each of the sites the team visited. Team members debriefed each other after each session, and the insights the team gained were transcribed in a running narrative. Sometimes site-visit team members would prepare a written report following the visit to share additional perspectives. The team asked the professionals at each science center what insights they wished to share, and reviewed some of the mathematics and learning research literature. The emerging research on cognition and learning presented in a 1999 report on learning by the National Research Council (Bransford, Brown, & Cocking, 1999) was especially persuasive. This research has provided new and deeper understandings of how people learn, which has implications for the work of science centers. [22].

Science Centers produce various kinds of mathematics exhibits, programs, and materials that serve multiple audiences.

The science center field has demonstrated the capacity to provide engaging mathematics exhibits, programs, and materials. Five cities were visited by the team to detail the work of six institutions and some team members took side trips for quick looks at other institutions[23]. The lists below note the range of displays, programs and materials found, as well as the various audiences served.

Mathematics in Science Centers

Displays, Programs, and Materials	**Audiences**
exhibits	preschool
workshops	K-12 school groups
curriculum	parents and families
kits	inservice teachers
trade publications for general use	preservice teachers
web sites	university faculty
programs in schools and classrooms	general public

[22]Although there is more to be considered about how people learn than can be presented here, the research was helpful in thinking about the implications of what was found. In particular, the research findings about transfer of learning—for example, knowing how and when to apply what is learned in one context to a problem in a different context—are relevant to the work of science centers in mathematics. The research on how people learn suggests new ways for mathematics teaching and learning and provides a strong motive for the contribution of science centers.

[23] Dallas' Science Place, COSI Toledo, and Paris' La Cité des Sciences et de l'Industrie. These were opportunistic visits, as they were close to sites selected for this study or accessible because of personal vacation travel.

Science centers add an important experiential component to the formal mathematics instruction provided by schools.

Science centers provide an important experiential component to accompany the formal mathematics instruction provided by schools, although this connection is not always exploited by school educators, parents, or science-center professionals. Research on learning (Bransford, Brown, & Cocking, 1999) indicates that knowledge obtained through a variety of contexts supports what is called "flexible transfer and fluent access." Essentially, this means that people are more likely to extract relevant elements of what they have learned and are better able to apply them in new settings. However, the transfer must be activated in some fashion. Often the activator is a teacher, a parent, or a science center staff member who draws the learner's attention to a relevant item. High-quality exhibits can also elicit this transfer.

An example may make the point better. One visitor interviewed by the author shared this story:

> *I had learned the Pythagorean Theorem in school. I knew the formula $A^2 + B^2 = C^2$, but I didn't get it until I was playing with a science center geoboard. The staff person suggested I make a right-angle triangle with a rubber band, then for each side make a square with the triangle line being the base of the square. So I made three squares—one on each side of the triangle. The staff person said: Count the number of little squares included within each big square. I did and when I realized the number of squares in the two squares on the sides equaled the number of little squares (in the square) on the third side—I realized what the formula meant. I then reworked the original triangle and repeated the process. I discovered the Pythagorean Theorem all over again.*

Observations made in the case studies support our assertion that science centers have the capacity for contributing to improved knowledge and understanding of mathematics—even as the need for additional staff development for science center professionals is acknowledged. Science centers can provide real-world connections for mathematics and help answer questions such as "Why do we need to do algebra?" The site visit teams concluded that because science centers are hands-on, they can support the formal instruction provided by schools. By working together, conceptual understanding of mathematics is enhanced. Mediated mathematics experiences—initiated by a helpful person, an engaging exhibit, or useful and fun activities— can contribute to reversing negative or "can't do" attitudes found among children and adults.

Linking exhibits and programs to NCTM and/or state Standards makes the science center a valuable resource for the K–12 school population.

Across the nation, state departments of education are calling for standards-based education that is coupled with tests of varying significance for K–12 students. The use of Standards in designing exhibits, programs, and materials can be a benefit to the teachers in schools and to parents wishing to support mathematics learning of their children.

In this study, half of the science centers generated their exhibits, programs, or materials based on either the NCTM Standards or the state mathematics standards. That is, when considering what to create, they went to the standards first and designed around the concepts. This approach was used by Pacific Science Center to construct the exhibits and the lessons for the *Mathfinder* van and by Ann Arbor to develop the *Geometry* exhibition. It was also part of the *EQUALS Investigations* development process.

Alternatively, science centers can link exhibits, programs, and other materials, such as kits or web sites, to the Standards after they are built. This approach will help illuminate for the visitor what elements of mathematics are being addressed. It also tends to result in a broader diversity of exhibits and a less targeted focus.

Either approach gives the visitor the benefit of knowing where the learning and experiences fit in with a defined core of knowledge. The intentional use of Standards gives the staff a focusing device and seems to result in multiple and deeper explorations of a given concept. This is precisely opposite from what is often found in American mathematics curricula, which continue to be "a mile-wide and an inch deep" [24] (1997).

Highest-quality exhibits, programs, and materials come from "intentionality" — where the products are designed in accordance with a particular philosophical or theoretical position and with commitment to achieving the intended outcome.

The intention and philosophical orientation of the science center make a difference in its approach to doing mathematics. While this may seem obvious, it was discovered that the results were more subtle and complex than this statement suggests at first reading.

Most importantly, where the exhibit and program quality in mathematics was highest, it was found that there was an intentional focus on what the visitor was learning, as opposed to what the exhibit or program was "teaching." In other words, exhibit or curriculum designers appeared to evaluate their products with questions such as "What does the visitor learn through this experience?" Looking not only at what visitors do, but also at what they seem to understand allows the designer to refine the exhibits or materials until what the learner does and understands matches the intent of the museum educator and the designer more closely.

[24] This phrase was used in the curriculum analysis provided for the Third International Mathematics and Science Study (TIMSS).

There is a parallel orientation in some schools that are working toward standards-based education. That is, by focusing on what children learn, teachers are learning to improve their teaching strategies and children are making greater progress[25]. It is clear that in the science-center field, the museum can find a niche in which it contributes to the community and its work in a constant refinement of that role. For example, Lawrence Hall's focus on equity has caused the science center to grapple with equity issues through multiple efforts. With each new program offering, they refine their understanding of what it takes to achieve equity. Mathematics programming was one more step toward equity. Likewise, the Exploratorium grapples with notions of inquiry, and Fort Worth wrestles with what it means to construct "extraordinary learning environments."

A substantive philosophical framework gives science center staff a touchstone to evaluate the work they do. It is also likely to draw visitors because people develop expectations about the nature of the experiences they will encounter. A framework counters perceptions of superficial amusement, increases depth of experience, and enhances the credibility of the institution with funders looking for more than entertainment values.

The human resource—the staff and its advisors—is the science center's most valuable asset for engaging in mathematics conversations and experiences.

The depth of talent and experience of the staff and advisors made a difference in the quality of mathematics exhibits, programs, and materials offered. This finding may correspond to the earlier finding about product quality, perhaps in part because the intentionality—or corporate culture—of the science center is learned.

The expertise, intellectual wisdom, and artistic and technical talent of science center professionals combine to make exhibits and other science center programs and materials credible and interesting. Successful science centers hire and retain staff whose values and experiences match the values and focus of the museum. At the same time, these effective science centers select projects that best utilize their staffing talent.

Alternatively, science centers sometimes decide to do a program or project and assign staff based on availability, rather than the preparation that individuals bring to the area. Although this may be necessary because of employment practices or other concerns, the findings from learning research suggest an issue to consider here: Expert knowledge comes with organized conceptual schemas that guide how problems are represented and understood within the domain (Bransford,et.al, 1999). Furthermore, different domains require different approaches for learning. The implications for science centers doing mathematics mean that they must address the staffing or design-team issue.

The talent question was addressed in several ways, including acquiring the necessary expertise by relying on a team of talent used as advisory personnel, such as outside mathematicians or mathematics educators, perhaps through short-term contracts with them. A note of caution, however—the content oversight for mathematics must be sustained and have a strong voice in the exhibits, programs, and materials design in order

[25] In a 1999 conversation with Greg Hall, the former Assistant Superintendent for Assessment in Alberta, Canada, Hall attributed the success of Alberta schools in mathematics on the TIMSS assessment to adopting and implementing the NCTM Standards.

to work. When it is not present, the design can slip away from content accuracy, away from the intended focus, and even toward unintended misconceptions.

Having credible content expertise is critical, as is having expertise in learning. A knowledge of pedagogy is important, especially in crafting curriculum. The most successful exhibits seemed to reflect a kind of knowledge the developer has that may be akin to Shulman's pedagogical content knowledge[26] (Ibid). That is, good exhibit design accounts for the ways people engage exhibits and learn from phenomena and seems to precipitate actions that are likely to activate connections among concepts. Might there be a techno-pedagogy that underlies the technology of exhibit design? Designers who applied technical and mechanical expertise with an artist's perspective help to create attractive and enticing exhibits.

Finally, for science centers, critical friends are essential. Either uninvolved staff or invited outsiders are needed to review exhibits. Where this practice occurred with mathematics exhibits and programs, the result was visitor or user experiences that more closely matched the intent. When this type of feedback is overlooked, exhibits, programs, and materials may miss the target and may even create misconceptions in the user. Sometimes the designers whose ideas are being tested may be unable to see how the exhibits, programs, and materials are being used because their intentions cloud their perceptions.

In general, the site visits revealed these insights:

- Competitive salaries and benefits are important for reducing turnover and the need to retrain constantly.
- Providing time to think and reflect allows staff to create better exhibits, programs, and materials.
- Encouraging professional growth makes a difference in keeping staff, sustaining their enthusiasm, and providing a stimulus for improving exhibits, programs, and materials.

Science centers choose to do mathematics exhibits, programs, and develop materials based on what they already do well.

The most effective outcomes happened when the science center grew the exhibits, programs, and materials out of their own strengths. For example, Pacific Science Center already had a statewide van program with operational funding. To suggest a mathematics-focused van meant they could rely on a known and successful delivery

[26] Pedagogical content knowledge requires that the teacher own the content knowledge of a discipline in a way that includes information about barriers or difficulties a learner must overcome to understand the concepts. According to Shulman, it is not sufficient to know the content and generic teaching strategies, since different disciplines require different strategies in order for students to construct meaningful understanding.

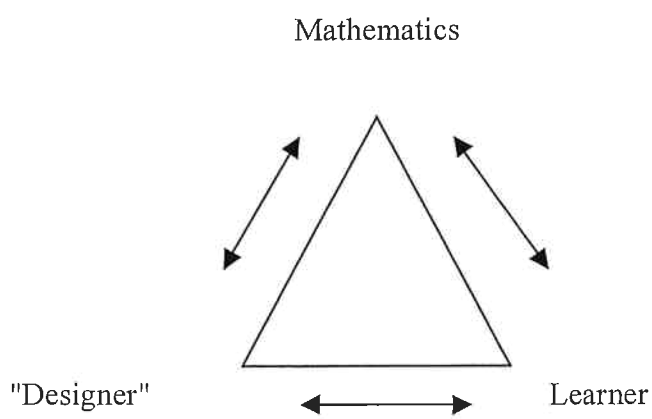
format and concentrate on transitions to a new content area. Also, it is appropriate that science centers start small and learn from the experience.

Exhibits, programs, and materials are more successful and effective when relationships are built with end users as partners who are equal contributors to the outcomes.

Mark St. John, of Inverness Research Associates, provided Fort Worth with a framework for considering the relationship of the science center with the content it provides and the visitors who use it. Fort Worth has utilized this framework in developing programs and exhibits[27]. This technique is a useful tool when thinking about the appropriate involvement of others during the design process and in thinking about the potential role for science centers in K–12 mathematics.

Begin with the triangle of relationships shown below. The arrows reflect the intellectual relationship the learner must develop with the content, the expert knowledge the designer has, and the pedagogical knowledge that connects the designer (of either exhibits or experiences) with the learner. The connecting arrows are the critical element here, because they reflect the process of creating, defining, and nurturing the relationships.

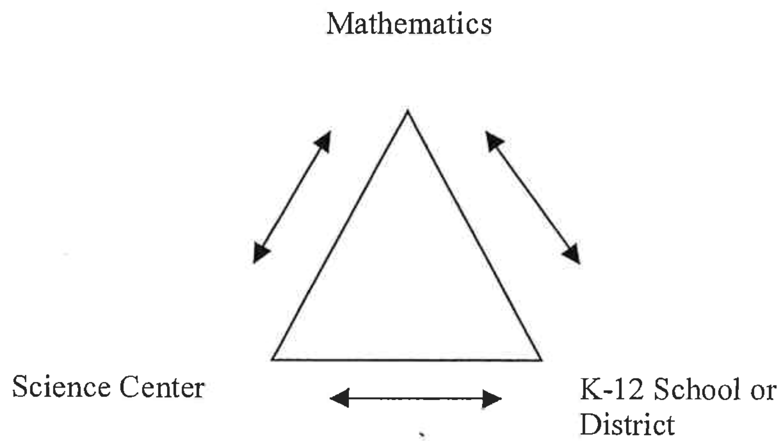
Framework of Relationship



The site-visit team discovered in its work that there is an extension of the idea of relationships in the model above. From talking with the different science centers, the

[27] From Mark St. John, in conversation with Fort Worth staff.

team discovered that the entities at the triangle vertices could change and could be used to define other important relationships. For example, in the mathematics triangle, substitute "the K-12 education system" for "learner" and "the science center" for "designer," since it is important to think of the science center as existing within a complex system of relationships. This gives an additional perspective for placing mathematics within science centers.



Once again the connecting arrows point to the relationships (and partnerships) that invigorate the exhibits, programs, and materials. The team found that the more successful mathematics programs came from institutions in which more than cursory attention was paid to the process of partnership. These institutions were better able to meet the needs of the audience, and the relationships further defined and secured a particular niche for the science center.

Paying attention to the connections between the science center, the K–12 system, and mathematics helps to sustain the science center's presence in the minds of parents, teachers, and community members, as well as of funders—be they government, corporate, or philanthropic.

Although the potential is enormous, there is almost no research or evaluation of mathematics learning in science center exhibits, programs, or materials.

Generally, science centers do not conduct research on the design or outcomes of their exhibits or programs. Often funders will request an evaluation, but frequently the data are not published in a manner that serves the field. Despite asking at each site, the team was unable to obtain any significant research or evaluation findings from the science centers visited. The science centers did share anecdotal stories about what visitors did and said about exhibits or programs and occasionally about the benefits accrued from the experiences.

Emerging Issues

A lot of questions surfaced during the study and stimulated long, thoughtful discussions. Some of the questions, responses, and insights shared during the study are presented below. These are some of the issues to be addressed, should science centers proceed with a mathematics agenda.

How to choose topics?

The TIMSS reports gives one measure of information about what content is needed. A review of the TIMSS findings (*A Sourcebook of 4th-Grade Findings: TIMSS*, 1997) showed that U.S. 4th grade students had more difficulty on measurement, estimation, and number sense than their international counterparts. In 8th grade (*A Sourcebook of 8th-Grade Findings: TIMSS*, 1997) Beaton et al., 1996) students scored lower on geometry, measurement, and proportionality when compared to other nations. At the 12th grade level (*Mathematics and Science Literacy in the Final Year of Secondary School*, 1998), the TIMSS items were selected for "mathematics literacy" and represented multiple domains. The design and reporting of achievement scores makes specifying content challenges difficult, and since at the 12th grade, students performed poorly on the exam it makes sense to focus on the content areas of previous known trouble.

Most of the science centers visited were already addressing several of the most difficult sections of the TIMSS test. For example, Ann Arbor developed a geometry exhibit and Pacific Science Center targeted measurement in its van programs. However, during the discussions with educators, the team found a strong need for support in the area of number sense—specifically, helping children develop solid understanding of multiplication, division, and, most important, fractions and decimals. Frequently, the achievement failures do not *begin* at middle school, but rather it is at middle school that the lack of understanding becomes apparent.

Local school districts and/or state education offices also have needs to be met in mathematics. Typically, schools have annual tests that describe the achievement of students. The results from these tests and information from districts can provide deeper details about what is needed at a local level.

There is an interesting point to consider regarding topics. Asking people what they *want* is an important approach; considering what people *need* may set science centers onto a different pathway. People need higher-order mathematics, but science centers reported that parents want remediation (i.e., drill and practice) for their children.

Should we address mathematics directly?

Choosing to do mathematics with science center exhibits may mean reviewing extant exhibits, programs, and materials and unpacking the inherent mathematics. The Exploratorium is thinking along these lines. Or it may mean choosing to do an explicit mathematics exhibition, where each component targets a particular concept, as in Ann

Arbor's *Geometry* exhibition. Or, it might mean deciding that all future exhibitions will address both science and mathematics, as they typically work together. This approach is the direction Fort Worth intends.

What is the role of NCTM or state Standards?

Content choices might be considered in light of either the NCTM Standards or the state's Standards or frameworks. A free-choice, informal learning institution is not obligated to follow structures that schools follow. However, doing so ensures that two particular audiences—teachers and parents—will have a powerful reason to pay attention and to bring schoolchildren to the museum. Obviously, teachers would find such support advantageous, especially in this time of high-stakes tests. Parents can also support their children's learning of mathematics when good, interactive exhibits help illuminate concepts.

As noted above, the National or State Mathematics Standards can provide a framework for choosing appropriate content for exhibits. They can also be used to entice new audiences to the science center, such as teachers of mathematics or parents seeking to improve their children's achievement in mathematics. There is another reason for using the Standards to frame exhibits or other science center exhibits, programs, and materials—that is, to deepen the mathematical literacy of the general public.

The Standards define what a mathematically competent individual needs to know and be able to do. Children are not the only ones who need to attain higher levels of performance, as reflected by the Standards. In this rapidly changing economy, which relies increasingly on technology, technical competence, and extraordinary problem-solving capacity, many adults find their own knowledge base in mathematics quite limited. Unfortunately, there are few places or mechanisms by which to learn mathematics informally. Lay people get access to significant amounts of science interpretation through science centers, television, radio, newspapers, and magazines. There is nothing parallel for mathematics.

What does learning theory suggest?

Another factor influencing content choice comes from what is understood about learning. Developmentally, people engage ideas—make meaning—first through action, then with images (imagination), and finally through symbolic manipulations (Reynolds, 2000). Experiences support the developmental sequence of how people engage with ideas. According to Sherry Reynolds:

> *Piaget noted...the advantage of the development of cognition is that it frees us to think without having to actually do things..... This ability is potential, in the sense that it does not develop unless the person has had opportunities to engage in that kind of thought and to attempt to solve problems that will develop it.*

Thus the areas of most (academic) challenge may be the content areas that require more active manipulation and application of imagination. In other words, if learners are challenged in understanding proportionality, then what might be needed are hands-on exhibits in this domain that would support concept development.

How do science centers get and keep visitors interested?

The team found that more sophisticated mathematics engaged science center visitors longer in solving problems, provided the exhibit required interaction from the visitor. Complex mathematics explaining a visual phenomenon resulted in short, almost nonexistent time on task. Where complex ideas were presented so that visitors could manipulate the variables, visitors spent significant amounts of time. For example, computer simulations with fractals[28] engaged visitors for significant time periods.

Getting the visitor to notice or pay attention to exhibits can be challenging, particularly as some visitors—mostly children—race from object to object. Ultimately the visitor settles down and shifts from context building— getting the lay of the land—to more sustained investigation with something that catches his or her attention. Humans constantly and simultaneously process incoming sensory information. What triggers attention is typically something new or something unexpected. This is the novelty effect.

The novelty effect can happen when something familiar includes a new dimension. For example, there were multiple variations of the Normal Distribution exhibit in several science centers. However, in a side visit to Dallas' Science Place, the team noted this same exhibit designed with an additional element. It used table tennis balls and glass pegs, so that as the balls dropped a musical sound was produced. Around this exhibit there always seemed to be a crowd of visitors who watched through more than one cycle. The exhibits seemed to attract more visitors than similar examples observed elsewhere.

What should we call it?

One of the interesting, unanswered questions from this study is whether to inform visitors at the beginning that they are doing mathematics. Using a friendly title may entice visitors into trying the activities. However, a major problem in mathematics today is that people have not linked activities or experiences in mathematics with traditionally understood terminology for specific concepts. This leads to confusion and misunderstanding. For example, in Washington State the EALRs used the term "Spatial Sense," but parents forced the framework developers to revert to the more commonly understood "Geometry," because the selected terminology did not convey meaning to the adults.

The familiar and iconic may convey meaning in a way eye-catching titles may not. However, initial reaction by many public visitors suggests that mathematics terms evoke

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[28] The author observed the fractals exhibit at Paris' La Cite des Sciences et de l'Industrie, which was not part of the study, but was visited during the time frame for the study.

unpleasant memories and result in people's avoiding the exhibition. Might market research better inform this decision? Would a public relations campaign generate more enthusiasm for mathematics language?

What would it mean if science centers did mathematics the way they do science?

If one looks at the 4^{th} grade science achievement on the Third International Mathematics and Science Study (TIMSS), U.S. students scored in the top third of nations (above average) in the international comparison. In contrast to science success, mathematics in the United States has not fared as well. The findings showed that U.S. students are average in mathematics during the elementary years, but decline significantly in achievement by the end of high school.

Some researchers have argued that NSF's substantial investment in elementary science education and informal science institutions' strong focus in supporting elementary teachers and students in science learning are factors contributing to science success.

Crediting science centers with even a small piece of the science achievement on TIMSS opens the door to this question: What if science centers offered more exhibits, programs, workshops, and publications in mathematics—perhaps equal in number and emphasis to their science offerings? Would there be greater achievement in mathematics?

Recommendations

The United States needs and wants improvement in mathematics accomplishments. Achievement has benefited from the introduction of Standards, but the goal is still out of reach. Science centers, as part of the educational infrastructure (St.John, 1996) can make a significant contribution by providing informal mathematics learning experiences.

The primary recommendation from the team for ASTC is that the organization undertake a capacity-building initiative that would enable science centers to offer more and better mathematics in more institutions nationwide.

Should ASTC choose to further mathematics development in the science center field, an initiative might include the following elements:

1. A showcase (conference or workshop) of the current, best mathematics exhibits, programs, and materials in science centers.

The team has identified some, but not all of the mathematics exhibits, programs and materials currently in the field. There are others. To encourage museums to take up more mathematics in their institutions, it is recommended that a hierarchy of steps running from least formidable to more complicated be employed. Some of the steps might be:

- Organizing in-house discussions about mathematics, with assistance from local mathematics educators
- Using or copying a mathematics-based exhibit from another institution
- Adding mathematics to exhibit text for existing science exhibits
- Offering *FAMILY MATH* type classes
- Including a few mathematics-based exhibits when conceiving a new science exhibition
- Developing mathematics-based exhibition programs
- Offering after-school classes or adding a mathematics segment to regular after-school science classes
- Sponsoring teacher workshops with others as leaders
- Offering short teacher workshops
- Seeking funds for more extensive work with teachers.

There appears to be sufficient interest to hold a working conference that would allow professionals to examine the exhibits, programs, and materials available, to discuss some of the questions raised by this study, and to give science center employees an opportunity to imagine and create new products. At the same time, funders could be invited to the showcase to excite them about the possibilities. A number of federal agencies, foundations, and corporations have already demonstrated interest in improving the state of mathematics literacy in the United States. In addition, foundations that consistently express concern for children and their learning experiences may find that new avenues for improving mathematics understanding constitute a desirable project.

2. Staff development for science-center professionals seeking to include mathematics in their exhibitions, program offerings, or materials.

Part of the current dilemma is that science centers do not have many mathematics educators, mathematics enthusiasts, or mathematicians on staff. Learning mathematics, as portrayed by the NCTM Standards, will be an important first step. Several strategies appear tenable. A series of institutes, such as those offered by the Teacher Educators Network[29] during the early 1990s, would deepen the capacity of educators and exhibit designers to think about mathematics.

Alternatively, sending staff on extended site visits to work with those already engaged in doing mathematics has a powerful learning value, as this SGER-supported project has demonstrated. Finally, although ASTC conferences already include sessions on mathematics, mostly as exhibit or program components, it might be productive to include a few sessions where mathematics is explored explicitly.

3. Creating working relationships with the National Council of Teachers of Mathematics and the Mathematical Association of America.

ASTC has formed many successful, fruitful partnerships in the past. Although individual science centers can and do build relationships with local teachers groups, there is a powerful statement made when national organizations agree to collaborate. Furthermore, by building the relationship, the organizations create fertile ground for new ideas.

4. Creating a presence for mathematics by inviting mathematicians or mathematics educators to address the field.

Nationwide, there are interesting, exciting, and easy-to-understand mathematicians who are seeking to improve public understanding of mathematics. Individuals who might be considered include authors whose works have stimulated public interest in mathematics or have addressed the all-too-common fear of mathematics. In addition, the mathematics education community can be a rich source of people who are passionate about mathematics and learning.

[29] A grant from NSF in 1990 provided funds to ASTC's Teacher Educators Network (TEN) to conduct three inquiry institutes for science center–based teacher educators and partners from university faculty and/or classroom teachers. There was also a fourth, follow-up institute.

5. Finding out if doing mathematics in science centers makes a difference in visitors' learning or attitudes about mathematics.

There has been almost no research completed that examines the effectiveness of informal learning experiences in mathematics. Children's television programming, such as "3 2 1 Contact," has looked at learning outcomes and been able to report success. However, since few science centers have done mathematics, and fewer still have completed evaluations of exhibits, programs, and materials, this is a natural area for research.

6. Reaching out to universities, colleges, education organizations, and the K–12 school system as partners in achieving improved mathematics understanding by children and adults.

In exploring the world of mathematics education, a number of institutions proved to be very eager to work with science centers. However, as noted before, it boils down to building relationships. For example, hosting initial meetings, agreeing to explore ideas, fostering trust and patience, and negotiating the rough waters experienced at the confluence of two or more cultures are all part of collaborating to achieve an outcome.

For help in brokering these relationships it is suggested that science centers connect with their regional Eisenhower Consortium for Mathematics and Science. While many consortia members have reached out to the informal science community, for this SGER project the Eisenhower Consortium for Mathematics and Science Education at SERVE (South Eastern Regional Vision of Education) demonstrated how the Consortium's brokering role may be used to further a mathematics effort between science centers and schools. SERVE identified people, provided resources, and contributed mathematics expertise for at least one site visit and for the initiating meeting held in Edmonton, Alberta, in October 1998.