Scientific Studio Proposal:

THE VIRTUAL MUSEUM AS SCIENTIFIC STUDIO

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Originally appeared as Note 99-01, Mitsubishi Electric Research Laboratories

Abstract

This proposal was originally titled, "The Virtual Museum as Scientific Studio," and was prepared in November 1996. At that time it was a proposed collaboration between ITA, the MIT Media Lab, the University of Colorado at Boulder, and participating museums. The approach described in the original proposal has changed somewhat, but the vision is the same and the goals have been reformulated to strengthen the focus on interactions between the physical and virtual domains. The current collaboration is between Carol Strohecker and Michael Eisenberg.

THE VIRTUAL MUSEUM AS SCIENTIFIC STUDIO

A PROPOSED COLLABORATION BETWEEN
ITA, THE MIT MEDIA LAB,
THE UNIVERSITY OF COLORADO AT BOULDER,
AND PARTICIPATING MUSEUMS

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November 1996

We propose to develop a learning environment that brings adults and children together for activities based on tenets of science and math. Physical and virtual tools, places, and artifacts comprise a “Scientific Studio” that supports communities of museum-goers. By emphasizing connections between scientific activities and artistic creation, we aim to produce an environment in which people develop understandings that will ground further scientific study.

PROPOSAL:

THE VIRTUAL MUSEUM AS SCIENTIFIC STUDIO

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THE VISION

We envision a museum environment that relies on connections between virtual and real-world activities. Constructive learning activities clarify ways in which topics that seem to be different can nevertheless share important characteristics.

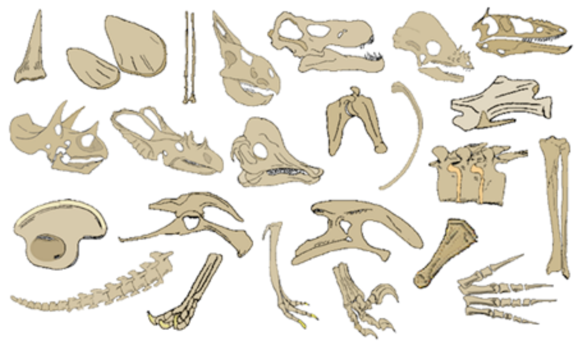
A hub of the environment is a distributed software system that children and adults use to create animated creatures, mobiles, and mathematical paper sculptures. Museum visitors also learn about ways in which these different constructions employ the same conceptual base. Principles of math and science that characterize the behavior of an object in one environment domain reappear when the object is used in other domains.

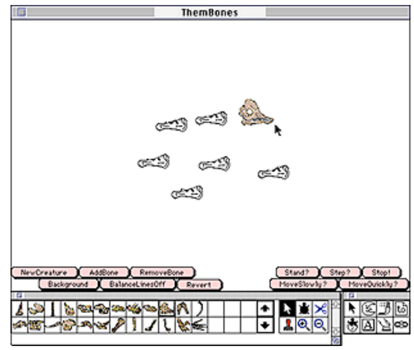
We emphasize the importance of aesthetics and craft as participants make things for themselves and for others, through a variety of media in both software studios and real-world museum workshops. Our vision is best characterized in terms of integration: integration between software modules, between activities in virtual and actual settings, between museum visitors' crafting of objects in software and in physical materials, and between "artistic" and "scientific" styles of thinking.

SCIENCE KITS AND THE DISTRIBUTED SCIENCE MUSEUM

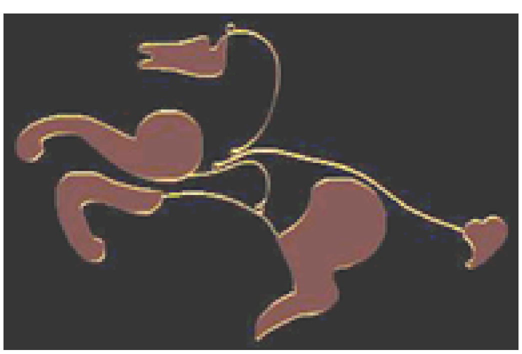
The distributed software system will extend three existing kits by developing their interrelatedness of concept and functionality:

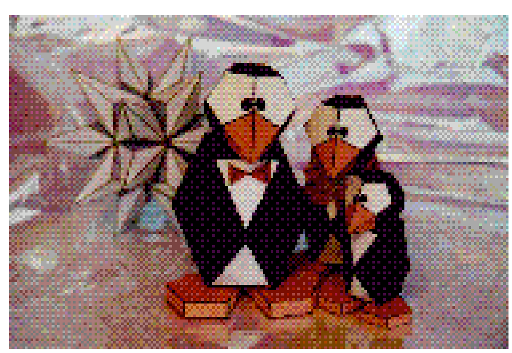
ThemBones is a "creature construction kit" that can be helpful in thinking about balance, an aspect of motion study. With this kit, learners put dinosaur bones together and then test the skeletons to see if they can balance while standing or moving. The software calculates the creature's center of mass and uses it in tests for static balance. The crux of these tests is the relationship between the center of mass and the placement of the creature's legs. Each object in the construction kit is characterized by a few simple properties: it has its own center of mass, a mass value (or weight), and a position. These three properties are used in calculating whether a skeleton will maintain its structural integrity and balance as it moves.





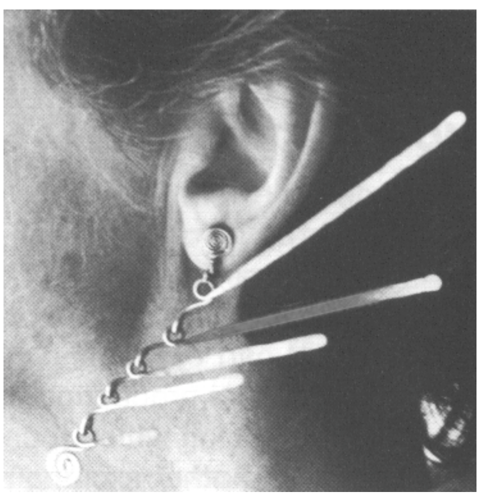
The **Artificial Artist** is a robot sculptor that designs kinetic mobiles in the style of Alexander Calder. The mobiles are semi-abstract portraits of animals, whose physiques it examines for dramatic poses and musculature using computer vision techniques. Although the system is autonomous, it invites participation at every stage. Users may make small adjustments or substantial design decisions; the system ensures that the result will be an attractive working mobile, either simulated in virtual 3D or fabricated in CNC-milled steel. These collaborations set the stage for learning about a wide range of mathematical and scientific concepts at work in mobile design, drawing from anatomy, geometry, mechanics, topology, and morphogenesis.





HyperGami is a software environment for the creation of paper sculptures such as polyhedra and origami; it allows children and adults to design and decorate "folding nets" for paper constructions on the computer screen, after which those nets may be sent to a color printer and folded into a wide variety of three-dimensional forms. HyperGami supports activities of design and construction in the medium of paper sculpture, weaving together both computer-based and "real-world-based" skills. Instead of hurrying students through material that assumes (and perhaps exacerbates) a short attention span, HyperGami promotes a style of activity that is refreshingly patient and contemplative. Moreover, while designed to be accessible and interesting for children, the system is based upon a full-fledged programming environment, and is thus rich and complex enough to be of interest to professional artists, mathematicians, and designers.

In the Scientific Studio, visitors can find such environments for making skeletal creatures, kinetic mobiles, and polyhedral forms. Visitors can design and visualize the forms online, often constructing them from smaller, rudimentary parts. They can show the constructions to one another and experiment with their behaviors: mobiles swing and sway as they balance, dinosaur-like creatures teeter as they move according to different speeds and gaits, and polyhedra enlarge to become landscapes or flatten into lattices, the edges becoming fold lines for paper constructions in the real world.



From J. Lipman & M. Aspinwall, Alexander Calder and His Magical Mobiles. *New York: Hudson Hills Press with the Whitney Museum of American Art, 1981.*

Visitors can also work with physical models to enrich understanding and appreciation through hands-on experimentation. The leap from virtual to physical can be assisted by computer-controlled fabrication of parts, possibly using technologies as prosaic as modified inkjet printers. With computer-assisted fabrication, visitors can turn their virtual designs into physical mobiles, paper sculptures, and creatures. Their creations can be small enough to be jewelry and ornament or large enough to be toys and sculpture.

Some of the constructions can become part of exhibits in the physical museum. Such exhibits further develop the Studio's themes of structure, natural morphology, center of mass, symmetry, scale, motion, balance, and gait. Visitors' creations can form the entirety of an exhibit or complement exhibits showcasing work by accomplished artists. Other constructions can find their way into people's homes, as souvenirs or as gifts to friends and family members.

The Scientific Studio is based on the idea that a good way to understand a concept is to see it at work in different contexts. In physics it is important to see that conservation of energy is at work in the arc of a baseball, the return of a swing, and the orbit of the planets. Similarly, concepts such as balance, spatial partition, and mechanical constraint play key roles in all three aspects of the Scientific Studio. Visitors can move fluidly between virtual studios. As they move, the visitors can bring their virtual constructions with them. These objects carry information about their own design and connections to related constructions, both online and off.

In this way users can, for example, explore the relation between center of mass and dynamic balance in both the mobiles and bones modules, or see how varied symmetries generate different kinds of polyhedra, mobiles, and skeletons. The projections from one studio could be motivated purely by appearance; a user may take her horse from the polyhedra world to the bones world, for example, and there be enticed to experiment with gait and balance. Or the projections could be based on deep analogies proposed by a virtual studio – for example, between systems of leverages in mobiles and supports in skeletons.

The Scientific Studio supports such learning activities with its complementarity of virtual and real-world tools, partnership of personal and public spaces, support for shared objects, and emphasis on transparency of objects and processes. Users may annotate their creations. Objects may open up to reveal the code that produced them. Visualizations of processes like center-of-mass calculations and the formation of shape edges may add liveliness as well as providing an alternate form of explanation. This sort of transparency aids learning and sparks curiosity; it is as much an invitation to experiment with the kit as a strategy for learning. The kits will also use visualizations to provide contextualized online help and to generate suggestions for further constructions.

ANTICIPATED RESULTS

• Our efforts will lead to a new kind of integrated museum environment in which virtual and real-world exhibits, tools, and activities support learning about aspects of math and science through a focus on craft and artistic sensibilities.

• We will develop three virtual studios within a distributed software system. In these studios, users can design kinetic mobiles, sculptures to be folded in paper, and dinosaur-like skeletons that walk. These artifacts share strong connections through their bases on concepts in topology, kinematics, dynamics, scale, and morphology. Users will be able to explore such concepts as they emerge in the course of creating. Visualization strategies will make transparent the scientific and mathematical principles at work, and objects can be exchanged between studios to augment their behaviors and characteristics.

• We will articulate a method for developing software that can extend the environment and others like it. Strategies for scaling up address common conceptual and programmatic “building blocks” that people can use for constructing things in distributed environments.

• The integrated museum environment will become a base for generating research data in the fields of sociology, anthropology, developmental psychology, and cognitive science. Because of its conceptual grounding, constructive activities, and connections to the real world, the environment can support studies of communities’ appropriation of technologies, as well as studies of how certain understandings of math and science develop.

A SCENARIO

At a local science museum, Yani and her brother find an area called the "Scientific Studio." The space is filled with people, computers, metal, paper, beads, glue, cardstock, paints, and other materials. Some of the people are engaged in discussion, some in quiet concentration, and others in various constructive activities. Nearby exhibit spaces display things that museum visitors have made, as well as related historic and explanatory objects assembled by museum personnel and visiting artists and scientists.

Tad and Yani wander into the space and watch as two people connect the last piece of a mobile to the larger hanging structure. Tad lingers and begins collecting tiny objects to put together as a smaller version of the mobile. He wants to assemble them as a dynamic brooch for his grandmother.

Yani gravitates toward the computers. She sees some young people and their father looking at an animal on the screen. Moving closer, she sees that the animal is really a dinosaur skeleton. The family members are selecting pictures of bones and putting them together to assemble the form. Yani looks around at the large-scale dinosaur skeletons in the surrounding exhibit area.

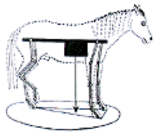
From D. Norman, The Illustrated Encyclopedia of Dinosaurs. *NY: Crescent Books, 1985.*

Then the family's computer creature comes to life! It lifts its legs in a distinguishable pattern as it scampers across the screen. A boy working at the next computer also has a dino skeleton running – but it manages just a few steps before crashing into a heap of bones. They laugh as Yani settles in front of another computer to make her own skeleton.

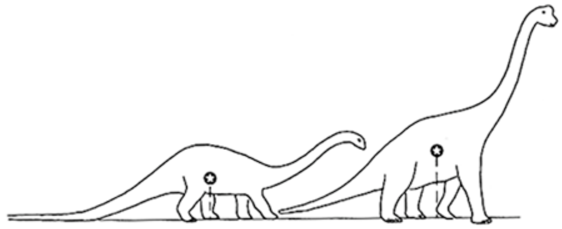
Yani realizes that she is entering a much larger virtual space than she'd seen on the screen. There are many Halls to explore, each with both a Gallery and a Studio space. The Gallery in the Hall of Dinosaurs displays some fantastic skeletal creatures, including the one Yani had seen the family working on earlier. As Yani browses through the menagerie, she gets some ideas for the skeleton she would like to make. A giraffe-like creature holds its head at an interesting angle, almost as if it were straining to hit a high note. She can imagine dramatic muscles on its graceful frame. Other creatures manage to convey senses of tension, power, and expressiveness, and Yani marvels at how such moods can be captured in still life. She sets some of the creatures into motion, noticing how those with pleasing visual proportions tend to move more smoothly than others.

As she dwells on each of the creatures, the system initiates comments and suggestions about them. It indicates that one of the creatures is rendered as a virtual mobile construction in the Gallery of the Hall of Mobiles; another creature triggers suggestions for trying experiments at home on the subject of how everyday objects balance; another cites tips on making balsa-wood skeletons; and still another suggests that its bones could be translated into paper models in the Studio of the Hall of Polyhedra. Yani keeps these ideas in mind as she makes her way to the Dinosaur Studio.

There, she selects some bones for her creature and carefully arranges them into an articulated structure. She spends time adjusting the angles at which the bones meet and adds touches of color. Finally Yani is ready to see how her virtual creature will move. She opts for a fast pace and, much to her delight, the creature trots to some cheerful music, leaving tracks along the way. When she tries a slower pace, though, much to her dismay, the creature crashes and crumbles. She would have thought that, surely, anything that can balance when it's moving quickly would be able to maintain balance at slower speeds! Yani queries the system and it illustrates an area over which the creature's center needed to align in order to maintain balance.



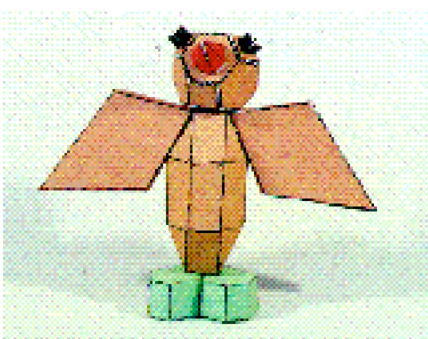
From J. Gray, How Animals Move.
Cambridge: Cambridge Univ. Press, 1953.



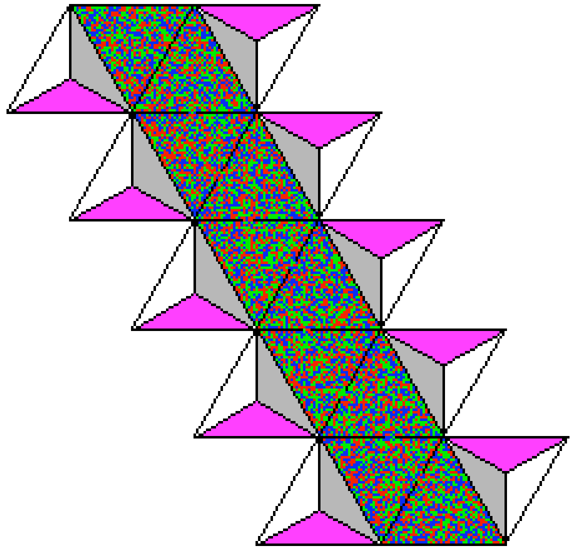
From R. McN. Alexander, Dynamics of Dinosaurs and Other Extinct Giants. *NY: Columbia Univ. Press, 1989.*

By adjusting the placement of two of the bones, she is able to move the center so that the creature ambles successfully in the next try.

Exhilarated, Yani decides to make her dinosaur out of paper so that she can take it home and show it to her parents. She duplicates the virtual creature, leaves one version in the Dinosaur Gallery so others can see and play with it, and then takes the creature with her to the Hall of Polyhedra. The Polyhedra Gallery is full of colorful polyhedral constructions.

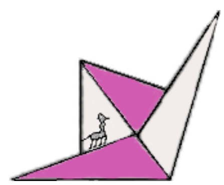


She sees some that she had once printed at home and folded into the tangible models now displayed on her bookshelf. As she looks closely at an unfamiliar polyhedral form, an octagon, the system animates it unfolding. First the polyhedron becomes translucent, so that Yani can see the hidden folds; then the form unfolds, until there is nothing but a flat plane criss-crossed with lines that she knows would be creases on paper.



Delighted, Yani shows the animation to a girl who is working nearby. They play the animation backwards and forwards, relishing the repeated folding and unfolding of the colorful form. They enlarge the polyhedron and watch as it takes on the scale of an expansive landscape, the colors having become even more vibrant.

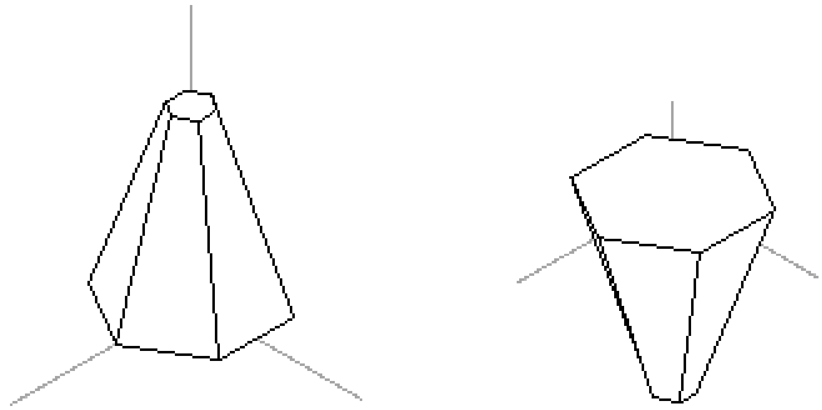
Yani places her dino in the scene and it begins marching along one of the edges of the polyhedron, which now seems like a horizon. The girls narrate excitedly as the creature traverses from one face to the next.[1]



When Yani enters the Polyhedra Studio, the system is able to "read" information encoded within her skeletal creature and provide clues for constructing it in paper. The system presents these clues in pictorial form. Soon it offers another image that bears a striking visual and conceptual resemblance to the center-of-mass alignment that she remembers

[1] This capability will enable our use of a research technique developed by Piaget and Inhelder ([1956, 1948], *The Child's Conception of Space,* trans. by Langdon & Lunzer, New York: W. W. Norton, 1967). When children imagine themselves as tiny creatures moving along an object like a knot – or, in this case, a polyhedron – the changed scales of space and time help them to better understand the spatial relationships inherent in the object. This feature of the Scientific Studio contributes to its potential as an research environment for cognitive science and developmental psychology.

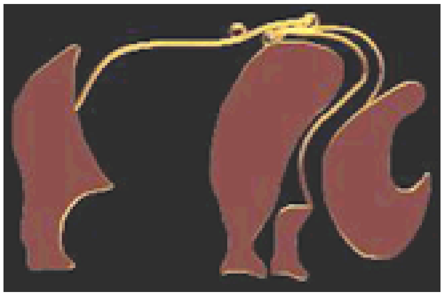
from the Dinosaur Studio. Yani can see that the truncated pyramid is more stable in the orientation at left than in the orientation at right:[2]



Thinking in terms of changing orientations and different possible ways in which a single construction can balance reminds Yani of the mobiles she encountered earlier, some of which included pyramids and other polyhedral forms. She finds Tad so he can visit the Hall of Mobiles with her. Yani "carries" her virtual skeleton model while Tad clutches the small piece of jewelry that he has made from beads and wire, which now resembles some of the constructions in the Mobile Gallery. The system again recognizes Yani's creature and suggests that she might use it as the basis of a virtual mobile.

Intrigued, she begins with some outline shapes derived from the animal's form. She tries to connect them with virtual wires to make a mobile, but the mobile doesn't balance and falls apart. The system suddenly displays some images of balance beams and blocks. Ideas of center of mass and static equilibrium enter into this situation as they had with the truncated pyramid and the virtual dinosaur. The system further suggests some easily-done experiments with homemade materials. Showing that balance beams can be hung to stand up, it demonstrates that for every mobile, there is an equivalent tower of blocks. Building and balancing with virtual versions of these objects, Yani engages with concepts of load and equilibrium, ideas that are also relevant for other activities in the Scientific Studio.

[2] (Assume that the force of gravity is toward the negative z-direction.)

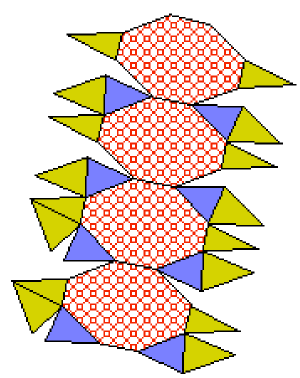


Returning to her mobile, Yani finds that it takes patience to try and balance all of the parts. While she works, the system indicates how the wires could be positioned to achieve proper balance. An animation of how the load is propagated through the mobile clarifies the structural changes.

But there is another problem. Sometimes there isn't room for wires, or wires cross. If that happens, the mobile won't work. In these cases the system offers views of various topologies, so Yani can see how the wires of the mobile partition space. As she works, the system suggests bends of the wires for visual effect, borrowing curves from the animal, smoothing contours, and making the mobile work mechanically. Yani can allow the system to complete the virtual construction automatically, or intervene to continue experimenting.

Since bodies, like blocks towers, carry load, the finished mobile can be used as the basis of a quickly wired, real-world creature. Yani develops the sculpture and then applies various paints and polishes. She tests her creation by blowing on it to see how it moves. Why, when twisted and blown around, does the mobile come back? The system offers further explorations pertaining to energy conservation and dynamic equilibrium, more ideas that tend to reappear in the Scientific Studio. Yani spends some time thinking about them and then places her virtual construction in the Mobile Gallery. She decides to leave her three-dimensional mobile in the exhibit area, with works by other visitors.

Realizing that it is time to go home, Yani collects the paper forms that she has accumulated: a set of dinosaur bones to assemble at home, and a printout of an unfolded polyhedral sculpture, which she plans on presenting as a puzzle to her mother. As she and Tad make their way through the exhibit area, with its impressive display of dinosaurs and mammals, Yani regards the gigantic forms with the discerning eye of an anatomist and artist.



RATIONALE

The Importance of a Sense of Connection to Objects and Materials

In his classic early 19th-century book *Democracy in America*,[3] Alexis de Tocqueville describes a New World society of energetic craftspeople who raised barns, tended fields, milked cows, pieced quilts, and addressed themselves to community living. We have come a long way from his image of a society in which people took this sort of "hands-on", "can-do" approach to life. As our late twentieth-century culture has become more reliant on technologies, both simple and sophisticated, most people have become concurrently less savvy about how the objects that they use were made, how those objects are maintained, and how they embody basic principles of science.

One might argue that there has been an obvious type of progress since de Tocqueville's day – many of the objects that we use are vastly more sophisticated, and often less expensive and better constructed, than those of the 1830's. But something has been lost in this transition as well: a sense of connection to the world and to materials. And something more may be lost, something touched upon in de Tocqueville's prescient description: namely, the cognitive benefits – in his words, the wider "circle of intelligence" – afforded by an easy familiarity with materials and crafts.

Many writers concerned with current technology see this increasingly "abstract" way of life as something to be celebrated. They see computers, microelectronics, and high-speed communications as ways of allowing people to transcend the age-old limitations of physical space and the human body. Despite the fascination in rethinking notions such as "a mile" or "an hour", our own view is that objects, materials, crafts, and the physical world should not be seen merely as "limitations" to be transcended. Rather, they remain important parts of our lives and can be enhanced by the growth of technology. Thus they can play an increasingly important role in education and human affairs.

Nowhere is the educational role of objects, artifacts, and materials more pronounced than in the history of scientific research and education. Typically, when people have first developed a new technology, the scientific principles that govern it have been apparent

[3] A. de Tocqueville [1835], *Democracy in America,* v.1, New York: Vintage Books Edition, 1990.

through the structure and working of the object. The old-style mercury switch is an example: it was, quite literally, transparent. One could see through the glass tube to the silver liquid and the contacts it connected when moving the tube to a level position. The more subtle principles of flow of electricity and conductivity were thus accessible at a glance; they were communicated through the structure and operation of the device.

Charles Babbage’s "Difference Engine" is another example. It was the precursor to his remarkable but never-realized design for the "Analytical Engine", arguably a full-fledged nineteenth-century computer. One visitor to Babbage's home, Sophia deMorgan, writes of the meeting between Babbage and the young Ada Byron (the future Countess of Lovelace, and Babbage's eventual collaborator):[4]

> "I well remember accompanying her to see Mr. Babbage's wonderful analytical engine. While other visitors gazed at the working of his beautiful instrument with the sort of expression, and I dare say the sort of feeling, that some savages are said to have shown on first seeing a looking-glass or hearing a gun.... Miss Byron, young as she was, understood its working, and saw the great beauty of the instrument." [p. 41]

Contained in this brief quote are several fascinating ideas: the notion that a scientific device can be described as "wonderful" or "beautiful"; that the instrument can present in a visible (if, in this particular case, not universally accessible) way the scientific or computational principles that it embodies; and that, importantly, it can play a motivational role in shaping the professional life of a young scientist. In effect, Babbage's instrument, while designed for genuine work and research, also played the role of a scientific demonstration or museum exhibit.

Unfortunately, few scientific or technological objects retain this sort of role in our lives. Under the (partly benign, partly damaging) influence of mass production, we lose the transparency and ease of access that once made technological artifacts into both practical tools and educational objects. Black-boxing, miniaturization, and other aspects of evolving functionality obscure the object’s scientific roots and create a distance between the scientific principles underlying the object, the object itself, and the people who use it.

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[4] D. Stein, *Ada,* Cambridge, MA: MIT Press, 1985.

In some cases, such as automobiles, this distancing has become so extreme that people can act more in service of the technology than the other way around.[5]

Important relationships have been lost in this process – understandings of the connection between science and technology, and the senses of ownership, appreciation, and even affection that people have toward crafted materials and objects. Technological artifacts should not be judged merely along the dimensions of efficiency, economy, or ease of use (though these are all important elements); they should be judged also according to how much they are capable of enriching our intellectual and emotional lives – how much they are able to widen our "circle of intelligence". In his marvelous recent essay "Why We Need Things", Mihaly Csikszentmihalyi writes of the roles that physical things play in our lives:

> Artifacts help objectify the self.... [O]bjects reveal the continuity of the self through time, by providing foci of involvement in the present, mementos and souvenirs of the past, and signposts to future goals.... [O]bjects give concrete evidence of one's place in a social network as symbols (literally, the joining together) of valued relationships. In these...ways things stabilize our sense of who we are; they give a permanent shape to our views of ourselves that otherwise would quickly dissolve in the flux of consciousness.[6]

We propose to create activities and environments that strengthen the links between science and technology education, on the one hand, and crafts and construction on the other. In this way, we would hope to foster a culture in which scientific objects can take on some of the roles that Csikszentmihalyi attributes to the favored objects in our lives – of memento, of souvenir, of symbol, of focus "of involvement in the present". We hope thereby to narrow the gap between technology use and technical know-how. Participating science museums will be the hubs of the effort. Activities in museums and in related virtual spaces will promote the development of *scientific studios* in people's homes and communities.

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[5] See I. Illich, *Tools for Conviviality,* Berkeley: Heyday Books, 1973.

The Importance of Making Things in the Process of Learning

Museum education typically suffers from a dilemma. A museum's success is measured, at least partially, in terms of numbers of visitors. Most exhibits and spaces must be designed so that many people can move through them quickly and easily. Unfortunately, this need interferes with possibilities for pleasurable, lengthy involvement with materials and ideas, the sort of involvement that is necessary for learning in any deep sense.

Seymour Papert has elaborated on these principles in his discussion of *constructionism*.[7] This is the idea that the act of *making* something – of constructing something personally meaningful – is particularly conducive to learning, especially when the activity happens in a supportive social context. Such contexts are often better developed in learning environments for arts and humanities than for math and sciences. Papert describes his wish that the experience of learning mathematics could be transformed from dull "school math" to the sort of aesthetic, constructive experience he witnessed when visiting a class in which children carved sculptures from bars of soap.[8] The children made shapes of their own fancy and worked on the project for many weeks, discussing their creations with others as they worked. The teacher and the students' families watched the forms gradually come to life and wanted to own the finished sculptures.

Painting in a studio is similar. Typically, the easels are arranged in a circle around a model. Each artist can spend hours or days at a time on her own painting. The canvas on each individual easel is an intensely absorbing private space. Yet, without hindrance or hesitation, each painter can easily look beyond the edges of the canvas to the model or to a neighboring painting. Other artists are within arm's reach, easily available for conversations, questions, comparisons, exchanges of materials, and so on. This sort of

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[6] In S. Lubar and W. Kingery (eds.), *History from Things*. Washington DC: Smithsonian Press, 1993.
[7] See S. Papert, *Mindstorms: Children, Computers, and Powerful Ideas,* New York: Basic Books, 1980; I. Harel and S. Papert, eds., *Constructionism*, Norwood, NJ: Ablex, 1991; S. Papert, *The Children's Machine: Rethinking School in the Age of the Computer*, New York: Basic Books, 1993; Y. Kafai and M. Resnick, eds., *Constructionism in Practice: Designing, Thinking, and Learning in a Digital World,* Mahwah, NJ: Lawrence Erlbaum, 1996.

partnership between private and shared spaces is key to the quality and resilience of the studio as an environment for learning.

In these examples, learning and production are not separate aims or activities. Rather, they are deeply intertwined, much as they are in Brazilian "samba schools," social clubs in which children and adults together learn, teach, create, and practice the dances they will perform at a civic celebration.[9] Many workshops and laboratories, often including science labs, have this quality as well. The environment we propose also encourages children and adults to work together, and combines learning and production – in fact, participants learn *through* production, in a supportive social context.

Because of the importance of "learning by doing,"[10] constructionist learning environments have come to include "construction kit" software as a primary genre. In our Scientific Studio, museum visitors will be able to use such kits in making mobiles, polyhedra, and animated creatures, but they will also be able to probe deeply into reasons why these apparently disparate objects are related. The software and the exhibits, along with workshops and other museum programs, will address basic principles of math and science and will support communities of learners in both physical and virtual domains.

The Scientific Studio creates a bridge between two types of learning environments: Science kits offer supports for learning through making things, but have no obviously related community to support demonstrations and discussions of the activities. On the other hand, while visitors to science museums can find other interested people, they cannot so easily find spaces that invite time-intensive, creative involvement with materials and ideas. Museum visitors typically observe and "interact" with exhibits and maybe even each other, but usually do not build or make anything. By situating construction kits within museum environments, the Scientific Studio combines advantages of each milieu.

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[8] See S. Papert, "Situating Constructionism," *Constructionism*, pp. 3-4.
[9] See S. Papert, *Mindstorms*, pp. 178-183.

Often, learning-environment developers see advantages of “virtuality” in terms of convenience or efficiency: gathering people in a virtual classroom is simpler than busing, a virtual chemistry lab is cleaner and less potentially dangerous than a real-world lab, and so on. We see other advantages in terms of complementarity and time: virtual experiments can be enmeshed with real-world activities to form a comprehensive learning environment in which people can develop concepts, techniques, artifacts, and discussions.

Thus we envision museum communities, both online and off, that converge as a culture of craft. Members of this culture employ the computer in returning to a sense of their own capability to deal with technologies. They also develop a deep sense of their own capabilities as learners: their know-how extends beyond skills in dealing with particular objects, to knowing what to do when confronted by unfamiliar objects or ideas. Adults and children alike have a better sense of what media to use and what activities to try in order to develop understandings of unfamiliar things.

SUMMARY OF THEMES

Finding delight in form - Things that hold an aesthetic fascination for people also hold mysteries for scientists and mathematicians. Our domains provide examples in the forms of mobiles, paper-folding, and skeletons.

Constructive learning - Museum visitors of all ages learn by creating things that intrigue them, along the way engaging a wealth of ideas that surround their enterprise. *Examples:* In crafting polyhedra for paper-folding, users encounter ideas about the mathematics of topology, symmetry, and projective geometry; in building creatures or making mobiles, users learn about morphology, balance, and mechanics.

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[10] See J. Dewey, *Democracy and Education,* New York: Macmillan/Free Press, 1916/1968, pp. 184-85.

Grounding - Deep mathematical concepts and physical principles reappear in new guises in very different contexts. *Examples:* Dynamic balance and center of mass are key to designing both mobiles that sway properly and creatures that can walk; partition topologies are key to finding both linkage patterns for mobiles and flat-paper patterns for 3D folded paper shapes.

Transparency - Objects and mathematical principles show how they work with the visual clarity of simple clockwork. *Examples:* Calculations involving balance and center of mass are made visible by animating force lines; polyhedral topologies are made visible by animating folds, marking crease-lines, and making the paper translucent.

Community - As in an artists' atelier, users borrow ideas and parts of constructions from each other. They share spaces in physical museums as well as in the virtual museum, spaces that are filled with works by other experimenters as well as by accomplished craftspeople. Each domain supports an accumulated wealth of design ideas.

BIOGRAPHIES

Matthew Brand is a Research Scientist and Lecturer at the MIT Media Lab, having recently received a Ph.D. in artificial intelligence from The Institute for the Learning Sciences at Northwestern University, where he was an NSF Graduate Fellow and a Graham Fellow. Brand studies the interaction between perception and meaning, in particular how computers can produce artifacts that are meaningful to humans. His research crosses computer vision, artificial intelligence, and developmental psychology. Recent projects include computer vision systems that sculpt mobiles and edit films using cognitive models based on theories about children's cognitive and perceptual development.

Michael Eisenberg is Assistant Professor of Computer Science at the University of Colorado, Boulder; he received his doctorate in computer science at MIT in 1991. His research interests include educational computing, mathematics and science education, scientific computation, and spatial cognition. Eisenberg is the developer of the HyperGami system, a program for the creation of polyhedral models and paper sculptures; and he is the author (or co-author) of over 25 papers and articles, a textbook *(Programming in Scheme),* and a published play ("Hackers"). He is also the recipient of a National Science Foundation Young Investigator Award; and while a doctoral student was the recipient of a Bell Labs Ph.D. Scholarship Award.

Carol Strohecker is a Senior Research Scientist at MERL - A Mitsubishi Electric Research Laboratory, in Cambridge, Massachusetts. She is concerned with how people learn and how objects, artifacts, and technologies can support the processes. Strohecker's doctoral dissertation (MIT Media Lab, 1991) involved a study of epistemological and psychological factors in learning about knots and the topological relationships they embody. Her current projects focus on the design and development of interactive stories and of software "construction kits" for learning about topics in science and mathematics. Strohecker has been a Fellow of the Harvard University Graduate School of Design, the Massachusetts Council for the Arts and Humanities, and the U.S. National Endowment for the Arts.

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