Middle Tech:
Blurring the Division Between High and Low Tech in Education

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1. Introduction: Blending Bits of Information and Bits of Stuff

In 1997 the most prestigious high school science fair in the United States—the Westinghouse Science Competition [Berger 94] —was won by Adam Cohen, then a senior at Hunter High School in New York City. Cohen's project, "Near-Field Photolithography", involved the construction of a home-built scanning tunneling microscope (or STM—a high-resolution microscope that uses the extent of quantum tunneling between a metal "reading head" and a conducting surface to map the contours of the surface). To build his microscope, Cohen not only programmed a home computer, but also employed a wide variety of quirky materials. As he wrote, "The mechanical structure of the STM used in this study is made of Lego (a plastic building toy). The Lego provides a rigid structure and shields the sample from air currents.... To isolate against high frequency vibrations, the entire microscope is encased in about 7 kilograms of plasticine (a kind of modeling clay). Bungee cords suspend the microscope from the concrete ceiling to isolate the STM from low frequency vibrations."[Cohen 97]

Bungee cords, plasticine, Lego, and digital electronics. Looking at Cohen's project, it is hard to draw any firm lines between "high" and "low" tech in this young scientist's work. After all, Lego, plasticine, and the rubber thread of which bungee cords are made are all relatively new materials: none of them existed a century ago. For Cohen's brand of science, then, there is only a spectrum of material: neither high tech nor low, but simply a wide range of available stuff—some of it on the old side, some new, some modular (like Lego), some moldable (like clay), some programmable.

The history of scientific investigation is deeply and profoundly woven with the history of crafts—of building and perfecting homemade or informal instruments, of creating new materials for new purposes, of putting old materials to new uses. Sometimes the scientist makes brilliant use of an everyday object—Ben Franklin and his kite come to mind, as does Helmholtz's description of Michael Faraday that "a few wires and some old bits of wood and iron seem to serve him for the greatest discoveries" [quoted in MacDonald 64, p. 16]. Or perhaps the scientist constructs an instrument (e.g., van Leeuwenhoek's microscope, Galileo's telescope) out of relatively newer or suddenly cheaper materials. Or, in another variation, perhaps the scientist invents a new material (like polyethylene) and only later comes to visualize novel uses for it. For such individuals, the world is filled with scientific objects, of all kinds; and this culture of craftspersonship confounds the educational theorists. After all, in the realm of educational technology, we tend to see computers (half-century old devices) as the epitome of "high-tech", and the rest of the material world as "low-tech". In the practice of real science, both among professionals and among students like Adam Cohen, the truth is considerably more complex, and more fun.

This chapter is an exploration of the notion of *middle tech* in mathematics and science education. Middle tech, for us, connotes two related ideas. On the one hand, the term suggests a panoply of new materials—temperature-sensitive films, cheap diffraction gratings, glow-in-the-dark dyes, fiber optics, reflective mylar—that sit somewhere between the obvious high-tech world of electronics and the obvious low-tech world of wood, clay, and stone. But middle tech also describes another notion—namely, the creative reinterpretation and integration of high- and low-tech educational materials. Rather than viewing computers as a world unto themselves, ethereal and abstracted from the realm of handicrafts, we prefer to think of middle tech as the unexplored terrain in which programs and materials, complexity and concreteness, blend into new media.

Our interest in this notion of blending bits of information and bits of stuff arose from our work in developing and using a software application named *HyperGami*. HyperGami is a program for the design and creation of polyhedral mathematical models and sculptures in paper; and as such it represents one approach to the integration of craft materials and computational media. We will use HyperGami in this chapter as a major source of ideas and issues for exploring middle tech, but HyperGami represents only one point in the vast space of design alternatives. There are many other craft materials to play with (and to invent), and there are many other ways of blending computation into those materials. In this chapter, we will attempt to look well beyond our initial work with HyperGami and to outline some possibly productive research and development themes for middle tech education.

The following (second) section of this chapter provides a brief outline and history of the HyperGami system, with the primary goal of providing a foundation for the issues raised in the remainder of the chapter. In the third section, we focus on the computational (as opposed to material) side of middle tech education, discussing how computers may aid in the design of new sorts of craft objects. The fourth section looks at the other, tangible, side of middle tech—describing how both new and ancient materials may be enriched by technology. In the fifth section, we take a step back and look at middle tech education as a whole; we discuss how this style of design can revitalize science and math education, and we use our experiences with HyperGami in particular to highlight some otherwise easily overlooked issues that emerge from the notion of middle tech. In the sixth section, we look toward the future, describing what we believe are fruitful directions for research in middle tech design; and in the final (seventh) section we conclude with some reflections on the insufficiency of "purely virtual" environments as the foundation of a rich educational experience in math and the sciences.

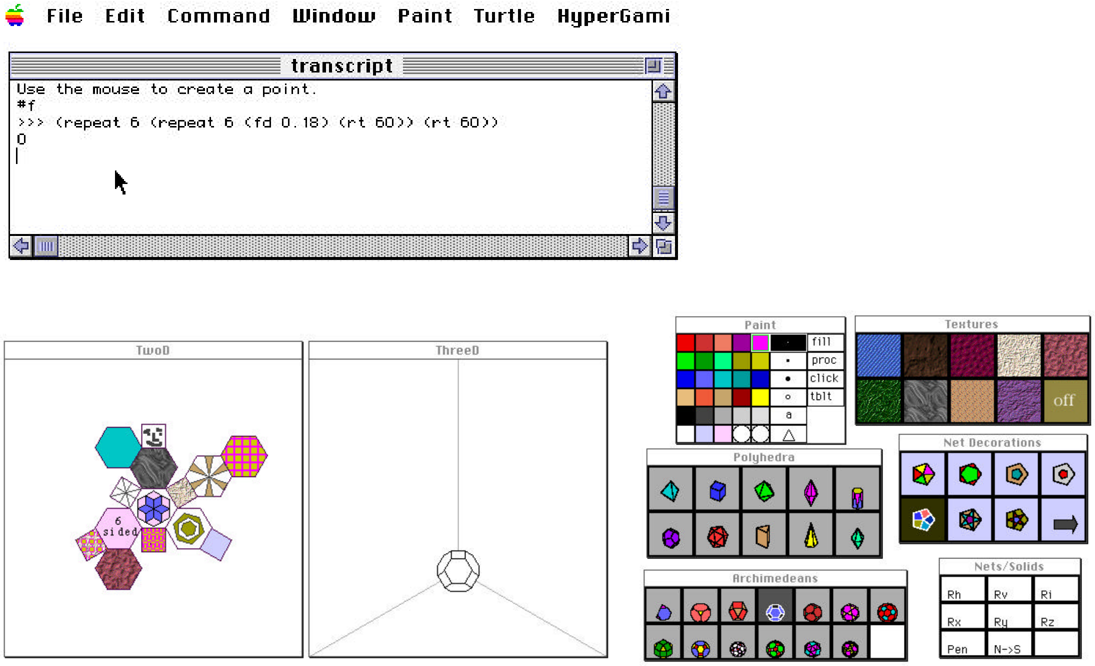
2. HyperGami—A Tool for Integrating Computers and PaperCrafts

2.1 An Overview of HyperGami

HyperGami is a software application designed by the authors and implemented in the MacScheme language environment[S2]; it runs on all Macintosh computers with at least 16M of memory. We have described HyperGami at length elsewhere [Eisenberg and Nishioka 97a, Eisenberg and Nishioka 97b], and so will only present a short description of the program here.

The essential activity in HyperGami is the design of customized three-dimensional polyhedral shapes, represented on the computer screen. These shapes may then be unfolded by the program into two-dimensional *folding nets*: flat patterns which can be printed out and refolded into the specified three-dimensional form. The HyperGami user may choose to decorate folding nets with an extensive variety of tools prior to printing; by this means, and by combining polyhedra together into composite forms, she can create an endless collection of decorated mathematical models and sculptures.

Figure 1 shows the HyperGami screen in the course of a typical scenario. Here, the user has selected a particular polyhedron—the truncated octahedron, one of the thirteen Archimedean (semiregular) solids—from the Archimedeans palette shown in the figure. The solid is shown in a three-dimensional rendering in the ThreeD window, and in its unfolded form in the TwoD window. The user has begun decorating the net using a selection of paint tools: some faces have been filled with textures, solid colors, or patterns; some have been decorated with hand-drawn lines; some have been decorated with geometric patterns; some with text; some with Logo-style turtle graphics designs. There are still other decorative options available to the HyperGami user: filling patterns may be defined via the extended Scheme language provided with the program (we'll return to this general topic in a moment); a recently-completed "surface turtle" package may be used to create designs in which a turtle executes a walk over the entire surface of the polyhedron (see [Abelson and diSessa 80], chapter 6, for an extended example of this idea); or the folding net may be saved and reloaded into other graphics applications.



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Use the mouse to create a point.
#f
>>> (repeat 6 (repeat 6 (fd 0.18) (rt 60)) (rt 60))
0
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Figure 1: A view of the HyperGami screen in the course of a typical scenario. The TwoD and ThreeD windows toward the bottom left show the folding net and three-dimensional rendering of a truncated octahedron, respectively. The folding net has been decorated with textures, patterns, solid colors, a hand-drawn figure, a turtle-drawn design, text, and geometric designs. The transcript window at top allows the user to type expressions into the MacScheme interpreter. The windows toward the bottom right include tools for choosing, decorating, and viewing polyhedra (several other optional windows are not shown).

Two major points deserve emphasis even within this telegraphic discussion of HyperGami. First, while the system provides the user with a large collection of starting polyhedra (including the five regular solids, the thirteen Archimedean solids and their duals, prisms, and pyramids), the true power of the program derives from the user's ability to create new customized polyhedra. HyperGami includes an extensive collection of mathematical operations that may be used to alter shapes in systematic ways—adding a new vertex here, stretching or shrinking there, and so forth. Figure 2 provides a simple example of the idea. Here, we have sliced the truncated octahedron into two halves and retained the upper half; this "half-shape" has been stretched vertically; and a "vertex cap" has been added to the top of the shape. Finally, the system has unfolded the newly-created shape into a folding net, which may then be decorated and printed out just like any other HyperGami net. Besides the operations shown in Figure 2, many other solid-customization operations are available to the HyperGami user. (See [Eisenberg 96] and [Eisenberg and Nishioka 97b] for more discussion of these techniques, and for discussion of limitations of the unfolding algorithm.)

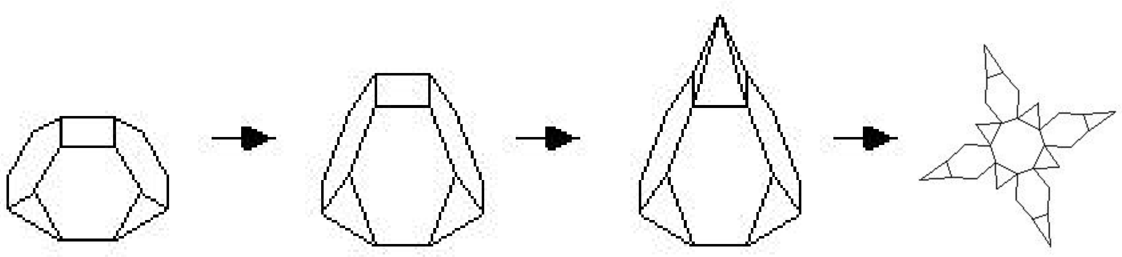

Figure 2: The top half a truncated octahedron (left) is stretched, then capped. The resulting shape is unfolded by HyperGami to produce the folding net shown at right.

A second and perhaps even more important point is that HyperGami is designed as a *programmable* application: it is built on top of the MacScheme system, and includes not only the core Scheme language environment, but also a huge and growing library of specific procedures and data types useful for the creation of polyhedral models. This permits the advanced HyperGami user to express ideas (e.g., new customization procedures) well beyond those directly built in to the original system. We will return to this issue shortly, both in the following paragraphs and in the third section of this chapter.

2.2 The Design of HyperGami: a Short History

Before moving on to a more general discussion of middle tech design, it is worth pausing at this juncture to provide a historical sketch of the HyperGami application in particular. It would be pleasurable for us to claim that we began with a clear vision of the system that we wanted to build, with a cogent set of requirements and specifications (as the software engineering texts recommend), and with a strong theoretical grounding in the integration of computation and crafts. Pleasurable, but not true. The actual history of HyperGami is considerably messier and less organized (and perhaps more interesting) than that.

HyperGami in fact began approximately five years ago as an addition to a graphics application named SchemePaint (created by the first author). The goal of SchemePaint was to demonstrate the power of programmable applications generally by integrating elements of direct manipulation interfaces with elements of interactive programming.[1] In particular, SchemePaint employed features typical of most paint applications (e.g., using the mouse to paint lines on the screen, or to select regions for filling with colors); but it combined these features with Scheme graphics primitives (e.g., for producing turtle-graphics designs). The resulting application lacked many advanced features of commercial paint programs, but it did permit users to create pictures with an appealing mixture of hand-drawn and "linguistic" (often mathematical) elements.

HyperGami, then, originated as a library of procedures within SchemePaint—a library geared toward the decoration of simple polyhedral nets and classical origami figures. and primarily aimed at students of geometry.[2] Since that time, the paint-application origins of the program have faded in importance, and the polyhedral-modelling aspects of the program have grown. What was originally a paint application has become, steadily and by degrees, a papercraft application.

There are several reasons behind this evolution of SchemePaint into HyperGami. First, we observed that both we and our students seemed to take far greater enjoyment in the creation of tangible papercraft objects than in the creation of computer-generated pictures. (We'll revisit this observation in section 5 of this chapter.) Second, as we explored the domain of polyhedral modelling in paper, we became progressively more fascinated in our students' understanding of three-dimensional forms; over time, this interest has blossomed into a much broader interest in spatial cognition, its development in children, and its role in mathematical and scientific thinking. Finally, we found that the domain of papercrafts provides fertile ground for experimentation in software. Thus, many of HyperGami's features have been designed with an eye towards the special needs and problems of craftspeople working in paper. A recent addition to the program allows the creation of "tabs" that aid in the folding together of solids; the program includes tools that help advanced users rearrange the folding nets that they create, making them easier to decorate or fold; and many of the decoration tools (such as the aforementioned "surface turtle", or the built-in geometric designs) are geared specifically toward ornamentation of geometric solids. ([Eisenberg and Nishioka 97a] and [Eisenberg and Eisenberg 98] include more discussion of these topics.)

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[1] See [Eisenberg 95] for a discussion—maybe an overly emotional discussion—of this idea.

[2] [Eisenberg and Nishioka 94] provides a relatively early description of the system.

Figure 3: HyperGami constructions. (Upper left) A HyperGami "pineapplehedron"; (upper right)a lattice figure composed of cuboctahedra (as nodes) and antiprisms (as struts). (Lower left)A polyhedral sculpture of a rooster by a middle-school student; (lower right) a duck with "radioactive green feet" by a fifth-grader.

Since HyperGami's beginnings, we have worked intensively with over 50 children (ranging from third to twelfth graders) on a wide variety of mathematical papercrafting projects; and we have made energetic use of the program ourselves, creating a gallery of polyhedral models and sculptures. Figure 3 illustrates four representative HyperGami objects resulting from this effort. Two are constructions of our own: a polyhedral sculpture (an "orihedron") of a pineapple, and a lattice structure composed of antiprisms and cuboctahedra. Two others are constructions by students: a sculpture of a rooster created by a 13-year-old girl, and a "SuperDuck" figure created by a fifth-grade boy. [Eisenberg and Nishioka 97b] includes much more description of work with students using HyperGami, and the website [W1] presents many more examples of HyperGami constructions (though these are still a small subset of those created by our students and us).

Are there any lessons in this history for the prospective designer of children's software? Perhaps. On the positive side, we have been pleased to see the rich intellectual rewards that followed from pursuing an offshoot of a (much more conservative) graphics application. And we regard it as especially important that we ourselves play with the software, just as our students do: rather than ghettoizing "educational software" as something designed by adults and used by children, we prefer to create tools that afford a wide range of projects suitable for elementary school students, high school students, undergraduates, and professional mathematicians. On the other hand, while there are some edifying morals to be extracted from the history of HyperGami, we would not want to portray the application as an unmitigated success story, nor as a shining exemplar of a sound design process in operation. The application is still, after five years, "homegrown software", and many aspects of its interface could benefit from an overhaul[3]; for our own part, we have focused a greater

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[3] We are currently at work on a reimplementation of at least a portion of HyperGami in Java; this should afford the opportunity to perform a thorough redesign of the interface.

portion of our energies on developing compelling examples, new curricular activities, and papercraft-related software features than on rethinking the fundamental design of the system.

3. Middle Tech Design: the Computational Environment

3.1 Computers in the design of mathematical and scientific craft objects

The HyperGami system represents one style of application design integrating computation and materials. Broadly speaking, this style of design emphasizes the use of the computer as a tool to expand the creative range of mathematical and scientific crafts. In the particular case of HyperGami, this expansion of creative potential occurs for three reasons. First, HyperGami allows the user to create a far wider variety of polyhedral models than would be possible in the absence of computational media. Non-computational polyhedral kits composed of pre-designed pieces (e.g., flat snap-together polygons, or plastic struts and joints) are capable of producing only those shapes whose faces or edges are given by the specific (and limited) dimensions of the pieces themselves. To take a simple example: a snap-together kit whose quadrilateral faces are all squares may be used to make a cube, but not an arbitrary rectangular prism. Of course, one could argue that this is an advantage of HyperGami's chosen material—paper—over plastic pieces; but a math student working in paper, and without a computer, is faced with the daunting task of creating a folding net for any shape that she wishes to create. HyperGami allows the mathematical crafter to describe and create complex, never-before-seen shapes precisely because of the combination of its eminently accommodating physical medium (paper) and the computational support that it provides.

A second important reason that HyperGami expands the creativity of the mathematical crafter is because it takes advantage of a range of computational facilities related to the central task of making polyhedral models. Specifically, HyperGami's decorative tools allow the user not only to create multicolored models but to do so in novel ways suggested by (or solely enabled by) computational tools. The HyperGami user may decorate models with solid colors, patterns, or textures; she may use the system's built-in tools to add complex geometric designs of various sorts to solids (as mentioned in the previous section); or she may read a HyperGami net into some other graphics system (e.g., Photoshop[S3] or Canvas[S1]) and decorate her net using the vast assortment of features offered by those other systems. It is because the computer is itself an instrument of such sprawling capabilities that it permits the user to take advantage of tools not only for the specific aims of creating a particular shape, but of enhancing that shape in hitherto unrealizable or unimaginable ways.

Finally—and perhaps most importantly—HyperGami's associated language offers a new and powerful medium in which to describe, express, and think about the shapes that one creates. As we and others have argued [Abelson 91, Eisenberg 95], a programming language is not simply a convenience for the user of a computer application, nor is it merely a tool with which to add new customized features to an application. Most crucially, a programming language is a means by which to express procedural ideas—perhaps otherwise hidden or subtle ideas—about some particular domain. In the case of HyperGami's expanded Scheme dialect, the language permits one to think about solid geometry in procedural terms. One may create new polyhedra via an "algebra of solids", starting from simple solids and performing sequences of operations upon them. Shapes are sliced apart into pieces, joined together at faces, stretched, shrunken, and capped; and any shape created by previous manipulation is a candidate for further manipulation. This is a style of creation peculiarly linguistic in style—the language of creation becomes in itself a language for the description of polyhedra. (A new shape, for example might be a "slice of an icosahedron, two of whose triangular faces have been exchanged and one of whose faces has been capped with a pyramid"—a description reflecting the sequence of procedural operations used to design the solid.)

This last point is perhaps worth dwelling upon just a bit longer. Computers enhance craftwork not only because they allow new physical artifacts to be created; nor only because they allow for more precision or more decorative options to be employed in those artifacts. Computers enhance craftwork most surprisingly because they allow for new languages, new formalisms to be developed around the creation of artifacts; and these new languages allow the student to think in novel, productive terms. Languages and notations are the media through which our thoughts are structured; and computers are tools by which new languages and notations may come to be considered as designed artifacts in their own right.

It is likewise important to note that these arguments, while derived from our HyperGami experience, do not at all depend on that particular example. Indeed, it is a fruitful exercise to think about other mathematical / scientific crafts, and to imagine how computational tools for design could extend those crafts in wondrous directions. What would a computational tool for the creation of new kaleidoscopes look like? Or a tool for the creation of tops? Or a tool for the creation of topological puzzles? Or a tool for the creation of balancing toys? In every case, we might begin by thinking along the three major lines suggested by our HyperGami example: the increase of potential complexity, the use of related computational tools, and the power of a programming language. A balancing-toy design system, for instance, might begin by allowing us to create (on the computer screen) novel asymmetric forms that, when realized in wood, will balance at the edge of a shelf or athwart a string (increase in complexity); it may allow us to experiment with new forms created by mixing together materials of multiple densities (increase in complexity); it may allow us to experiment with decorations of our creations (related computational tools); and it may allow us to imagine sequences or algebras of operations that alter or extend balancing toys in various ways while preserving their fundamental property of balance (the addition of a programming language).

3.2 Computers as advisors in the creation of craft objects

We ourselves have barely begun to explore the myriad ways in which computational design tools may lend themselves to new forms of mathematical and scientific crafts. But this is only one way in which computers may enhance the design of educational objects. Here, our ideas are shaped not by something that HyperGami does but by something that (in its current version) it fails to do—namely, to offer anything in the way of help, advice, or guidance to the student in the creation of some new form. The HyperGami user, when faced with (e.g.) an octahedron on the computer screen, may have no clue as to which interesting operations might be performed on this shape; he is simply left with an array of options, and while sometimes that array may be construed as an invitation to explore it may likewise represent a conceptual reef on which the novice craftsperson may founder.

We are currently at work on a collection of embedded *advisors* to incorporate within HyperGami—software tools to suggest potentially interesting geometric operations to perform upon solids. One such advisor , for example, examines a starting polyhedron to see whether it contains a planar set of vertices through which the shape may be sliced, as indicated in Figure 4 below. Here, we begin with an icosahedron (at left); the HyperGami advisor finds a set of five vertices through which the shape may be sliced (center) to produce the two component slices (at right). An advisor such as this is similar in spirit to the computational coaching facility pioneered years ago by Brown and Burton in their creation of the WEST system [Burton and Brown 82]; and it has a family resemblance as well to the "critics" incorporated in design applications by Fischer and his colleagues [Fischer *et al.* 91].

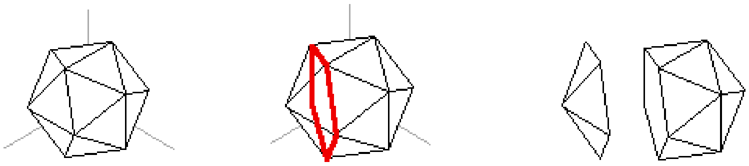

Figure 4: One of HyperGami's experimental "spatial advisors" in operation. Starting from an icosahedron (at left), a set of five planar vertices is found by the software advisor and identified for the user, who may then slice the shape through the suggested plane to produce the two pieces at right.

Space does not permit more than a cursory discussion of this topic, but the notion of creating useful craft advisors for middle tech applications raises a host of interesting research questions. First—looking back to the original WEST work, which focused on the identification of important "issues" that students should be aware of in playing a mathematical game—a craft advisor should crucially have some notion of what constitutes worthwhile advice. Why, after all, should (say) HyperGami's polyhedron-construction advisor suggest several operations but not others? Such questions inevitably lead to the larger task of attempting to formalize (but not rigidify) principles of good taste in design. And there are educational issues to be raised as well. Is the purpose of an educational craft advisor to suggest new directions for design—or is it perhaps more importantly to develop cognitive skills in the student? To take the specific case of HyperGami's polyhedral construction advisors: are these tools supposed to help the student create especially novel forms, or are they primarily aimed to promote specific skills in spatial cognition? Different answers to this question might well lead us, as researchers, to explore vastly different sorts of craft advisors in our work.

3.3. Computers as elements of crafted objects

While HyperGami does blend the use of computational media into the process of creation of crafted objects, it still maintains a sort of division between the "virtual" and "real" worlds. The HyperGami user employs the computer during the first (design) stage of her work, and then moves over into the physical world for the subsequent (construction) stage. While this division is perfectly appropriate for the sort of materials employed by HyperGami, it obscures still other directions for exploration in which computational media are themselves embedded within mathematical and scientific craft objects themselves.

Groundbreaking work in this direction was done by Druin [87] in her creation of NOOBIE, an appealing stuffed creature which served as the interface to a computer, though in this case only the system designer (not the users) took the role of "physical craftsperson". More recently, related ideas have been creatively pursued by Resnick and his colleagues at the MIT Media Laboratory in the incorporation of computational elements (the "programmable Lego brick" and its descendants) into scientific constructions of all sorts. [Resnick *et al.* 96, Umaschi 97]

Over the past year we and several colleagues at CU have employed the Media Lab's most recent generation of programmable brick (dubbed the "cricket" by its inventors) to create prototypes of scientific toys, kits, and exhibits in which computational and craft elements are blended. Figures 5, 6, and 7 show specific examples along these lines. Figure 5 depicts a "programmable kaleidoscope" (created by A. Warmack); here, three large mirrors are arranged in an equilateral triangle over a wooden base. When the user peeks over the edge of one of the mirrors, she sees an endless array of triangular prisms filling the space of her vision. A programmable motor is placed through the base so that it may churn up objects such as metal balls that are placed between the mirrors of the kaleidoscope; this produces a visually dynamic effect, suggested by the picture at right in Figure 5. Figure 6 depicts another example (this one created by T. Wrensch); here, a cricket has been programmed to move a pair of metal coils in oscillatory fashion, measuring any increase in current through the coils and thereby acting as a magnetic field detector (in much the same fashion as in Faraday's original nineteenth-century experiments). Finally, Figure 7 depicts a programmable color display (created by M. Burin, K. Johnston, and D. Olvera) in which programmable pumps alternately fill and empty three rectangular tanks with dyed water in red, yellow, and blue shades. By shining a light through the three tanks as they fill and empty in ever-changing patterns, one may see different colors shining through the tanks. All these examples (and numerous others that we and our students have made) illustrate the basic idea of taking some traditional scientific toy or exhibit—a kaleidoscope, an experiment in magnetic field detection, a color wheel—and seeing what happens when a bit of computation is incorporated.

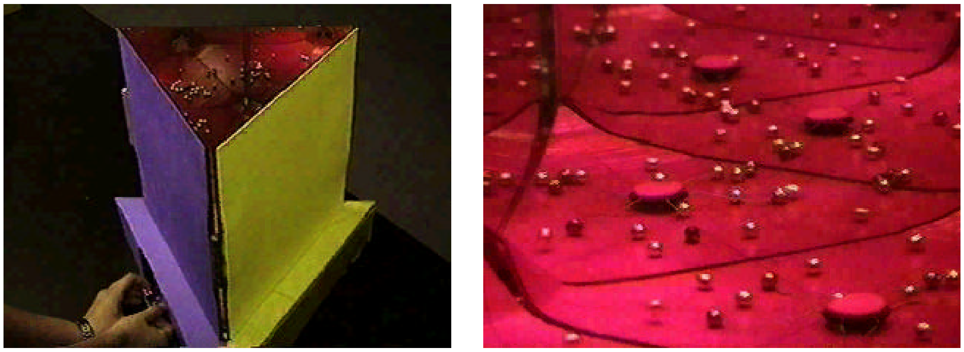

Figure 5. (Left) A view of a "cricket-enhanced kaleidoscope" from the outside. (Right) The view of the interior, reflected endlessly by the kaleidoscope's mirrors. At center is a cricket-operated motor which churns the objects placed inside kaleidoscope.

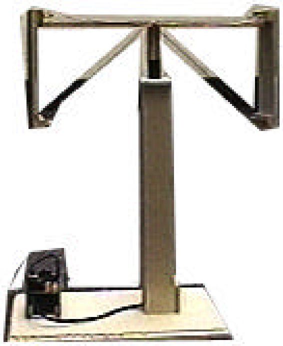

Figure 6. A cricket-operated magnetic field sensor. The cricket (bottom left) turns copper coils on the stand at right, and senses current through the coils to detect a magnetic field.

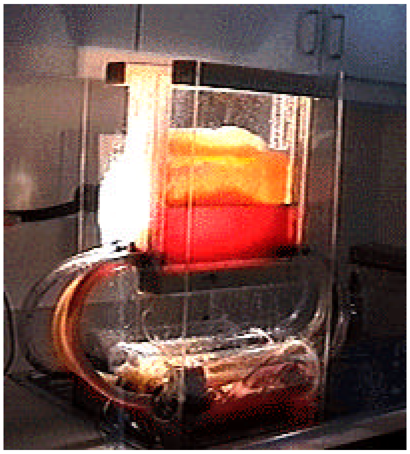

Figure 7. A cricket-operated color display. Light shines through three water tanks which are filled (via pumps) with blue, red, and yellow-tinted water. The pumps are operated by crickets, causing the water tanks to fill and empty in programmable patterns.

4. Middle Tech Design: the Materials

The previous section focused on the computational side of middle tech design, exploring the notion of computers as design tools, as advisory devices, and as elements of craft materials themselves. In this section we turn to the more explicitly material, tangible aspect of middle tech design.

4.1 The Evolution of Traditional Materials: Or, Everything Old is New Again

In our earlier accounts of the HyperGami system, we often found ourselves referring to the application as a blend of high tech (computers) and low tech (paper). Over time, we have come to revise our view—not about the "high techness" of computers, but about the "low techness" of paper. A visit to any large office supply store reveals that the range of expressiveness of paper—even restricted to those grades of paper available for color printers—is immense. There are relatively inexpensive grades; glossy papers; thick cardstock; papers in pastel shades; papers with background designs. And beyond these paper grades there are still other types that we have incorporated into HyperGami creations by gluing them onto already-constructed models: glow-in-the-dark adhesive sheets, holographic design paper, reflective mylar sheets. One grade of paper may be run through a color printer and transferred via ironing to fabric; this is usually employed for creating decorated T-shirts, but we have transferred folding nets to fabric and sewn them into the "pillowhedra" shown in Figure 8. There are still other types of experimental paper that we have yet to try in

HyperGami constructions: temperature-sensitive films that change color over a given temperature range, sheets with embedded diffraction gratings, paper that changes color when exposed to sunlight, polarizing filters, and so forth. In short, paper considered purely on its own is a medium that defies categorization as high- or low-tech.

Figure 8: "Pillowhedra" created from sewn fabric.

Indeed, many traditional materials are evolving in similar, wonderfully bewildering ways. While most elementary classrooms have a supply of yarn, there are now easily available glow-in-the-dark and magnetic strings—not to mention extremely strong Kevlar fibers, or the fiber optics cables and "muscle wire" described later in this section. Most children have worked with traditional paints; now craft stores market a variety of novel paints (including rubbery "3D" paints, glow-in-the-dark varieties, and "antiquing finishes" of the type used to make the copper-like polyhedron shown in Figure 9 below). Commercial kits for molding rubber into high-bouncing balls are available. Over and over, the uncharted possibilities for cross-fertilization with computational media are promising, to say the least: software tools might (say) model the dynamic behavior of a magnetic string design, or suggest ways in which glow-in-the-dark dyes might be combined with polarizing filters in new types of classroom sculpture, or help in creating rubber balls of non-uniform composition to provide customized patterns of bouncing.

Figure 9: A small stellated dodecahedron decorated with copper finish.

4.2 Materials Specifically for Science Education

The previous paragraphs focused on the ways in which even traditional low-tech classroom materials—string, paint, paper—have come to take on remarkably new forms. One may likewise turn one's attention to materials (some new, some old) specifically geared toward science education, just to see how those scientific materials might lend themselves to integration with computational media. Consider, for instance, the venerable crystal-growing kits, in which crystal structures accrete (typically over a period of hours or days) from saturated solutions. As far as we know, no one has attempted to employ computational control in the classroom to render these crystal kits more "customizable": conceivably, by using a computer to systematically vary (e.g.) the temperature, solute concentration, chemical composition, or mixing rate, one could create new or offbeat varieties of "crystal artwork". (At least such an idea is worth a try!) Fiber optics cables, not long ago the epitome of futuristic materials science, are now available at low cost, and suggest some potentially fruitful directions for integration with computational devices like the Media Lab's crickets:

whereas the crickets are designed to communicate "through the air", by sending infrared signals to one another, one might imagine instead an arbitrary network of crickets communicating via light signals in point-to-point fashion merely by rearranging patterns of fiber optics cables. Or consider the myriad uses to which inexpensive piezo films (which convert pressure to electrical current) may be put in creating touch-sensitive surfaces as interfaces to small computers. Just as the materials of the art studio offer new avenues for computational integration, then, so do the affordable materials of the classroom laboratory.

4.3 New Materials Well-Suited to Computational Control

There are several specific instances of new and affordable materials that seem especially ripe for integration in computational projects; we can't resist mentioning those materials here. One example is "muscle wire" (Nitinol) [Gilbertson 93], a nickel-titanium alloy that can be used to convert an electrical current into a powerful pull along a length of wire. This type of material seems perfectly suited to devising (e.g.) programmable marionettes or dynamic sculptures. Yet another family of examples are the various temperature-sensitive films and paints that change color within selected temperature ranges: by coating an arbitrary surface with a temperature-sensitive dye and using a computer somewhere inside that surface to gently heat or cool specific locations on the surface, one can make unique multicolored output devices. A less exotic but still potentially interesting example involves the use of iron filings suspended in transparent viscous fluid; such substances are marketed as ways of demonstrating magnetic field patterns in a manner that is easily seen in a sheet of paper or viewable on an overhead projector screen. By using computers to control the timing and placement of small magnets near these "viewable fields", one could easily create dynamic displays.

4.4 The Question of Cost

It should be noted that all of the sample materials mentioned in the previous paragraphs are available at relatively low cost—at least well within the budget of a modest home or classroom laboratory. In much the same manner as high tech digital electronics, the cost of middle tech materials is (by and large) dropping precipitously, so that even topics such as holography and superconductivity may be demonstrated through kits marketed at far lower cost than might have been imagined a generation ago.

Some middle tech materials are still at the research stage but are likely to become affordable in the foreseeable future. Recent work in computationally-enriched fabrics of various sorts—"wearable computing"—has garnered a tremendous amount of popular attention and interest [Mann 97]. Less glamorous but nonetheless fascinating work in basic material science has produced astonishing advances in such areas as the creation of synthetic diamond at prices that may ultimately be within the range of the home hobbyist.[Amato 97, p. 154] Overall, this burgeoning activity in affordable new materials—when combined with computational media—could, we believe, result in a marvelously democratic revival of the culture of serious scientific amateurism (the culture exemplified by pioneers such as Boyle, Lavoisier, and Franklin, all of whom explored scientific questions at their own personal expense). We will return to this issue in the following section.

5. Middle Tech in Science and Mathematics Education

5.1 The Cognitive Role of Middle Tech Materials

Consider the following typical scenario from an undergraduate astrophysics course: the professor describes the notion of an ever-expanding universe, mentioning that galaxies further from our own are rushing away from earth faster than galaxies close to ours. He goes on to state that this phenomenon of expansion is seen throughout the universe—i.e., that an observer within some distant galaxy would witness the same sort of expansion that we on earth do. Here, several students object: if we see further galaxies rushing away faster from us than do the closer galaxies, doesn't this imply that our own galaxy is at some sort of distinguished "center" of the universe? How could a distant observer experience the same phenomenon? The professor replies that there is no paradox, and by way of illustration takes a rubber balloon and some white paint; he paints an assembly of white dots on the balloon's surface; and then proceeds to blow up the balloon with air. As the balloon expands, the professor points out that, from the vantage point of any dot *D* on the balloon's surface, all the other dots are rushing away from *D* at a rate that increases with distance from *D*. No dot is unique in this respect.

The balloon demonstration is a staple of physics classes—a marvelously simple, low-tech illustration of an otherwise hard-to-visualize concept. But is the demonstration really quite as low-tech as all that? After all, rubber balloons—inexpensive toys for children—are made of a substance that has only come into widespread industrial use during the past century and a half.[Amato 97, pp. 49-51] Rubber balloons did not exist, either for children or scientists, in the mid-nineteenth century. Quite arguably, the very idea of a uniformly expanding universe would have been far harder to understand in the absence of material illustrations through which to seed the idea; at any rate, the notion would have undoubtedly been harder to teach.

Materials are the concrete, day-to-day, tactile illustrations of difficult scientific concepts. Rubber balloons illustrate the notion of an expanding universe; curves drawn on rubber sheets are used to illustrate basic ideas of topology. Pond water illustrates the transverse wave phenomena through which light waves are understood; metal springs illustrate longitudinal waves, as well as harmonic motion. When Kepler developed his laws of motion for the planets, he employed magnets as an exemplar of the idea of action-at-a-distance [Kearney 71, pp. 130-137]; Descartes used the image of fluid moving through a conduit as a basis for his model of reflex actions in muscles [Flanagan 84, pp. 1-3]; the first understanding of polarization emerged from the examination of the mineral calcite.[Halliday and Resnick 62, p. 1148] Paper is a good material approximation to a two-dimensional space, thread to a one-dimensional space; soap films illustrate minimal surfaces. The theory of evolution has traditionally been understood through the image of a thickly-branching tree, as eloquently described by Gould[96]; Freud's theories of the mind borrowed imagery from fluids under pressure.[cf. Baars 97, p.84] In this century, clouds and coastlines have been used as illustrations of fractal sets [Mandelbrot 88]; water dripping from a tap becomes an illustration of chaotic dynamics[Shaw 84]; froth or soap suds are said to resemble the large-scale arrangement of galaxies in the universe [Taubes 97].

Many, many more examples along these lines could be offered. Indeed, even the apparent counterexamples—those instances of scientific ideas not strongly linked with material illustrations—are striking for that very reason; arguably, it is the absence of obvious material analogies that make the theoretical ideas of quantum mechanics (especially those of wave/particle duality) so difficult to visualize. [Cf. the discussion in Miller 84, pp. 154-174.] And even the short list given in the previous paragraph demonstrates some interesting variety. Some of the materials and objects mentioned (water, froth, clouds) are "natural", occurring in the environment of every human culture; others (thread, soap, paper), while possessed of long histories, are nonetheless artificial, engineered materials. Importantly, these latter materials were not invented for educational purposes—there is no evidence that the earliest manufacturers of soap had any interest in the study of minimal surfaces—but once these materials became common cultural artifacts, they enabled still other, more abstract ideas to enter the cultural consciousness.

Everyday materials, simple objects, are more than carriers of potentially powerful scientific metaphors. They are also capable of emotional resonance, of being irresistible sources of wonder to the student of science or mathematics. Morgan's [88] book on the geometry of minimal surfaces opens with a marvelous photograph of the author as a tiny child watching with serious and rapt attention as his mother blows soap bubbles into the air. In a famous autobiographical anecdote, Einstein mentioned that his interest in science was piqued by an early gift of a compass [Bernstein 93, p. 161]. For some children, tops or gyroscopes become joyful illustrations of angular momentum; mirrors arranged into kaleidoscopes beautifully present ideas of symmetry; crystals are gorgeous, collectible snapshots of solid geometry. And even adult scientists derive wonder and inspiration from toys, objects, and gadgets. The birth of the Gestalt movement occurred when the psychologist Max Wertheimer found himself thumbing through a children's "flip book" and reflecting on the perception of movement that it produced.[Goldstein 89, pp. 193-4] Or, to take another example: the physicist

Richard Feynman reported in his autobiography [Feynman 85, pp. 157-8] that his Nobel-prize-winning work was first inspired by the visual image of dishes wobbling as they rotated.

For educational technologists, the immediate implications of these notions are twofold. First, the burgeoning world of new and affordable materials, new stuff, should be taken as an opportunity for an expanded repertoire of visual images and analogies; that is, we should be on the alert for difficult scientific and mathematical concepts that may suddenly become illustratable through the means of new things. Velcro, fiberglass, "silly putty", styrofoam, and so forth may be new concepts in the making, or old advanced concepts rendered comprehensible. Second, we should perhaps begin to regard materials, objects, and everyday stuff as artifacts that can potentially be designed, or redesigned, with an eye toward educational purposes. To some extent, the well-established tradition of scientific toys, kits, and exhibits already represents a step in this direction; but is it so much more quixotic to wonder whether the day-to-day materials of our culture could be looked at afresh, in the hope of making them more provocative, compelling, self-explanatory, or fun? Might not (e.g.) electrical wires be designed to somehow display the fact that a current is running through them? What if adhesives were designed to make a sound as they formed chemical bonds with the surfaces that they contacted? Might not string instruments be designed to somehow enhance the user's awareness of the vibrations in their strings; or might not drums somehow display the vibration patterns of their surfaces? We will return to these issues, and the role that computation might come to play in conjunction with them, a bit later in this chapter.

5.2 The Social Role of Objects—Examples from HyperGami

The previous paragraphs highlighted the cognitive (and to some degree the affective) role of objects and materials in science and mathematics education. For many educational technologists, this taste for the tangible, for the physical, might well be viewed as oddly nostalgic. Aren't animations, simulations, and virtual laboratories more powerful and expressive than any physical toy or object? Aren't cyberspace and virtual reality the educational and professional environments of the future? Isn't tangibility... well... a rather musty, obsolescent notion?

We have three major thematic responses to this sort of objection. First, the world is a rich and complicated place, capable of more than one cultural development at any given time. Simulations, virtual reality, and cyberspace have an undeniable appeal, and (from the educational standpoint) they embody some remarkable strengths in presenting scientific ideas. Often, the real world is not especially good at illustrating phenomena at very large or small scales. Simulations can help us understand the behavior of the unfamiliar, or of large and complex systems, or of systems evolving over long periods of time. None of this is controversial; and none of it contradicts the equally great potential, and appeal, for objects and materials in a full scientific and mathematical education. The world of educational technology, in short, can accommodate more than one intellectual development at a time.

Second—as we have argued—there are especially strong opportunities for integrating the strengths of computation, of simulations, of cyberspace, with the educational strengths of materials, toys, objects, kits, and exhibits. We will return to this theme once more in the final sections of this chapter.

Third, our experiences with HyperGami have convinced us that in fact there is a unique and special educational role for physical (as opposed to virtual) objects in the lives of young mathematicians and scientists. As computer scientists, we weren't initially very acute; these ideas actually crept up on us. It was only after working with our first bunch of students that we began to notice how real objects function over the course of an educational lifetime. We saw that our students would put their objects on display, or give them as gifts to adults. One younger student bestowed a nickname upon a polyhedron that she had built; another (somewhat older) student reported to us that he had proudly showed his HyperGami construction to his classroom teacher. Even our adult visitors, after viewing the program, would often ask to take a construction back as a gift for their children at home.

We began to notice, over time, how HyperGami objects—unlike most artifacts of a mathematical education—took on what we have referred to as "social currency"[Eisenberg and Nishioka 97a]; even mathematical objects such as HyperGami polyhedra have the potential of being souvenirs, expressions of affection, personal statements, and imaginary friends. We ourselves have used HyperGami constructions as wedding gifts, holiday ornaments, and thank-you notes. Virtual objects, in contrast, simply don't carry the same kind of weight, emotionally or literally (cf. the insightful essay by Csikszenthmihalyi [93]).

The fact that a physical object such as a HyperGami sculpture can just be *present*—can be in the room, unobtrusive, but noticed at odd moments—has a sort of importance that itself can be almost too simple to notice. When an object merely hangs out on the shelf, we find ourselves talking about it with visitors: we explain and re-explain the object from time to time. Or perhaps we pick it up in absent moments just to reflect on it anew. Most educational artifacts—and especially classroom software applications—are conceived of as having a built-in time clock: one uses the arithmetic program until one has mastered the skill (the quicker the better), and then one puts the program away for good. In contrast, a physical object has a hope of sticking around on the shelf for a few months, maybe a few years: the object first created by a fourth grader may be reflected upon all over again years later by an eighth grader. And while the eighth grader is now ready to view the object in a new light, she still imbues the object (particularly if it is a creative product, like a HyperGami sculpture) with emotional meaning. Objects have stories attached to them; they have personal narratives. In contrast, it is the rare simulation or virtual experience that could ever have the personal meaning of even the simplest keepsake or souvenir.

5.3 Middle Tech and the Culture of Professional Science

Our focus throughout this chapter has been on the role of middle tech in science and mathematics education. But it is worth pausing at this juncture to reflect on the culture of professional science as well. After all, middle tech is not a notion that applies exclusively to children or novices—it is an idea that could increasingly find expression in the lives and practice of professional scientists as well.

Indeed, we would argue that professional science needs a dose of middle tech. The past half-century of scientific research has been identified in the public mind with expensive, gargantuan, multiperson efforts: the Manhattan Project, the Apollo missions, the human genome project [cf. Galison 92]. It wasn't always so. When we think of seventeenth and eighteenth-century science (the "Scientific Revolution"), we tend to think of the individual, amateur scientist working out of his own home and laboratory: Robert Boyle, Antoine Lavoisier, Christian Huygens. Often, these individual scientists were wealthy men—only men were provided the education with which to participate in the scientific community, and few but the wealthy could afford the time and materials for scientific work. The opportunities, then, to practice science were anything but democratic. Nonetheless, there is a certain appeal about the practice of early science when compared to "big science": the resources of the individual could be sufficient to make huge progress, and the idiosyncratic taste and style of the individual shone in his work.

We believe —why pretend? We hope—that professional scientists in the next century may increasingly come to resemble their predecessors of the Scientific Revolution, at least in their ability to do important science on their own, in home laboratories and workshops. Twenty-first century scientists will be able to work with a huge range of new, relatively inexpensive materials—in conjunction with a huge range of inexpensive computational devices. (Just to mention Adam Cohen's Westinghouse Competition project once more: he estimated the construction cost of his home scanning tunneling microscope at a mere $50.) This second Scientific Revolution can be expected to be more democratic than the first. The cost of participating will be far less daunting than in the eighteenth century, and consequently the participants themselves are likely to be more demographically varied (and their styles and interests more widespread). While doing science may not soon, or ever, be universally affordable, it could well be as common a personal hobby as (e.g.) skiing or playing a musical instrument; and importantly, the quality level of amateur science could compare favorably to that of the seventeenth century pioneers.

6. Middle Tech: Potential Directions for Future Research and Development

6.1 Looking to the Future: the Materials Side

The past decade has seen a blossoming level of progress in materials science, including work on "smart" materials—i.e., materials endowed with (typically small but highly useful) elements of computational behavior (see [Amato 97] for a readable overview of this research). Likewise, there has been extensive and creative work in adding computational capabilities to furniture [Zimmerman et al. 95], clothing [Mann 97], and numerous other basic materials and artifacts. Perhaps only a bit more futuristically, Berlin and Gabriel [97] describe the notion of realizing computation in large numbers of elements in distributed media (they refer to the idea as "programming a cloud of dust").

While we see this work as exciting—even awe-inspiring—it should be noted that as a body of work it only partially overlaps with the notions of middle tech described in this chapter. First, our own preferences in material design run toward those which have some sort of educational use or intention. Materials, as we have argued, can be seen as tangible expressions of important ideas. A magnet evokes the idea of action-at-a-distance; a diffraction grating evokes ideas of wave interference; soap films evoke ideas of minimal surfaces. Merely making a material "smart" may not be especially useful from the educational standpoint, if the material fails to evoke these sorts of ideas or to promote productive imagery in its users. Indeed, one might view much of the research in "smart" materials as following in the (we believe unfortunate) tradition of embedding more and more incomprehensibility, more opacity, into engineered artifacts.

As a first research step, then, we would advocate studying materials from the educational/cognitive standpoint, a stance not usually taken in thinking about material design. What is it about certain types of "stuff"—craft materials, everyday objects, perhaps toys and kits—that gives them evocative power in science and math education? What is the role of working with materials—rubber, plasticine, paper, string—in developing mathematical or scientific ideas? Once we have a better understanding of materials as educational catalysts, we can begin to design new materials not to be more efficient insulators, fabrics, dyes, or whatever, but rather to make them more provocative, more wonderful, and more inspiring.

By the same token, our interest in "smart materials" is less in embedding computation *per se* within materials and objects, and more toward endowing materials with *expressive* computation—at least some measure of programmability, or communication with programmable media. Resnick and his colleagues' work, mentioned earlier, is directly in this spirit, but there are many more directions still to try. For example, craft work is characterized by the use of numerous small and cheap elements—hinges, screws, tacks, wires, paper, felt, adhesive, and many more. We believe that there is tremendous opportunity in adding very tiny amounts of programmability—perhaps a dozen instructions'-worth of program—in these widespread crafting elements. To take a few (admittedly speculative) examples:

- Programmable string or thread might (e.g.) be constructed so that it snaps or breaks after a certain discrete number of small tugs; for instance, one could program a "three-tug string" which severs itself after three pulls, a "four-tug string" after four pulls, and so forth. Alternatively, one might imagine a type of string that (upon some given signal, such as a tug), will stretch and contract itself in some sort of repeating pattern; string of this type could be used (among many other possibilities) to make a variety of marionettes with complex behaviors.

- One might imagine programmable thumbtacks which double as simple "button" inputs to craft objects—that is, if the thumbtack had a single ("flag") bit of memory, then pressing on the tack would set the flag to high, while otherwise the flag is set to a low value. In the same vein, materials (e.g., new types of felt or construction papers) into which the tacks are pushed might have simple means whereby they could read the values communicated by the embedded tacks.

- Programmable hinges might allow for simple dynamic motions (e.g., the hinges might periodically open and close, or might alter their state in response to, say, a light input). Such hinges might find especially interesting uses in scientific modelling kits like those used by students of anatomy: a "visible man" model containing a few tiny programmable hinges might be able to demonstrate the movements of muscles in an especially informative way.

Yet another direction might be to look at recent work in "augmented reality" [Feiner *et al.* 93], in which researchers endeavor to permit greater levels of communication between computer applications and physical artifacts, to enhance the expressiveness of middle tech scientific crafts. One might imagine, for instance, strings that can communicate (to a computer application) the level of tensile forces being applied to them; or perhaps adhesives might be designed to communicate the force with which they are holding two surfaces together; or a felt surface might be able to communicate a level of static charge. While some or all of these examples might be a bit fanciful, at least at present, we believe that the philosophy behind them is quite reasonable: they allow small increments of computational behavior to be distributed inexpensively throughout the types of craft projects that typify scientific education and homespun scientific work.

6.2 Looking to the Future: the Computational Side

On the computational side, we believe that the proliferation of middle tech materials and projects offers new directions for research. Certainly, it would be worthwhile to develop a greater range of powerful HyperGami-style applications to assist in the creation of homemade scientific experiments and instruments; in effect, we might ask what sorts of programs might be of assistance to the Adam Cohens of the next century. Computer applications could assist in the choosing of materials (alloy compositions, types of plastic, grades of paper) for certain construction projects; or programs might be able to take large lists of available materials—an inventory of those things that a student happens to have handy—and to suggest scientific projects or research areas that could be accomplished using those materials; or programs could assist with specific formalized aspects of more complicated craft projects (e.g., how to arrange a collection of lenses and mirrors to achieve a specific optical effect, or how to create a certain type of mechanical linkage).

At least some sort of development could readily be undertaken in making computer applications more powerful tools in the service of informal, homespun scientific and mathematical crafts. Pushing some of this research a bit more in the direction of artificial intelligence leads to the sort of efforts that we mentioned earlier in conjunction with HyperGami: i.e., developing intelligent "advisors" for scientific and mathematical crafters. Programs might assist students in the creation of topological or geometric puzzles; or they might advise students of graphics on the use and creation of visual illusions; or they might advise a student on how to create and maintain a terrarium. Rather than pursuing the traditional lines of AI research in creating "intelligent tutoring systems", one might imagine trying to create a line of "intelligent science project judges" that would assist students in building, presenting, and assessing entries in science contests; while research in this area might not produce truly automated science-fair judges (our guess is that it wouldn't), the effort could not help but yield new insights into the ways that science fair judges encourage—or maybe fail to encourage—the development of young researchers.

Another major line of research would look toward enhancing the computational infrastructure that contributes to middle tech education. It might become common practice, for instance, to endow the creations of scientific workshops with websites (much as one places a signature on a painting, or explanatory documentation beside a museum exhibit). In this way, students encountering home-crafted objects would have a standard means of finding documentation on the composition and creation of those objects. Likewise, science museums could take on an increasing role as local middle tech crafting centers, offering new materials to students for experimentation, and offering remote links to useful workshop equipment that could be made available to the public (e.g., high school students might be able to design customized plastic pieces on their school computers, and then retrieve the manufactured pieces at their local science museum). [Cf. the discussion in Eisenberg and Eisenberg 98.]

7. Conclusion: Filling the Room with Stuff, or, Why Virtuality Isn't Enough

Much of the last decade's writing about educational technology seems to imply a decreasing role for real, physical objects. Students are portrayed as increasingly virtual creatures, spending their time in virtual laboratories, taking virtual measurements, collaborating within virtual scientific communities, and communicating their results in virtual notebooks and journals.

It is strange that educational technologists, of all people, should be so cavalier about the need for physical objects in students' lives. As educational technologists—computer scientists—we have become aware over time of an emotional tension felt by many members of our profession: "yearning" mightn't be too strong a word. Computer scientists, after all, work with an instrument that remains majestically impervious in its outward appearance to all the labor that we bestow upon it. Day after day, the computer scientist returns to his or her office, and the computer looks exactly the same as it did a week ago, a month ago, a year ago. All the programming work, all the communication, all the email, all the documents, fit into a box that looks pretty much as it did when we installed it. Contrast the situation of the sculptor, the woodworker, the gardener, the mechanical engineer: these people's efforts are reflected, day by day, in their surrounding environments. Each day they return to work and see evidence of their creative and intellectual growth made manifest in the objects that they own and touch and stand among. It is perhaps the need for this experience that accounts for the poignant efforts that computer scientists make to reflect their work in their own environments—e.g., by putting screen dumps or conference poster presentations up on the walls.

Students of science and mathematics—at least many students, ourselves included—need to breathe the atmosphere of science and math in their surroundings. They miss the sense of wonder invoked by a setting: the local science museum, or the planetarium, or botanical garden. They need the sense of place experienced by the young Arrowsmith in Sinclair Lewis' novel [1925]:

> It was the central room of the three occupied by Doc Vickerson... This central room was at once business office, consultation-room, living-room, poker den, and warehouse.... Against a brown plaster wall was a cabinet of zoological collections and medical curiosities, and beside it the most dreadful and fascinating object known to the boy-world of Elk Mills—a skeleton with one gaunt gold tooth... The wild raggedness of the room was the soul and symbol of Doc Vickerson; it was more exciting than the flat-faced stack of shoe-boxes in the New York Bazaar; it was the lure to questioning and adventure for Martin Arrowsmith. [pp. 6-7]

In this chapter we have argued that middle tech is a broad notion that can revive this sense of excitement in the physical materials, objects, and settings of science. It points to the introduction of new materials, new objects, new scientific stuff for students to play with, and explores techniques of integrating these materials (as well as traditional materials) with computation. In doing so, middle tech can remake the surroundings of young scientists and mathematicians, enriching their lives by merging a sense of intellectual mission with a sense of physical place.

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References

[Abelson 91] Abelson, H. Computation as a Framework for Engineering Education. In *Research Directions in Computer Science: an MIT Perspective.* A. Meyer and J. Guttag (eds.). Cambridge: MIT Press, pp. 191-213.

[Abelson and diSessa 80] Abelson, H. and diSessa, A. *Turtle Geometry.* Cambridge MA: MIT Press.

[Amato 97] Amato, I.*Stuff* . New York: Basic Books.

[Baars 97] Baars, B. *In the Theater of Consciousness.* New York: Oxford University Press.

[Berger 94] Berger, J. *The Young Scientists.* Reading, MA: Addison-Wesley.

[Berlin and Gabriel 97] Berlin, A. and Gabriel, K. Distributed MEMS: New Challenges for Computation.*IEEE Computational Science and Engineering*, Jan-March 1997, pp. 12-16.

[Bernstein 93] Bernstein, J. *Cranks, Quarks, and the Cosmos.* NY: Basic Books.

[Burton and Brown 82] Burton, R. and Brown, J. An Investigation of Computer Coaching for Informal Learning Activities. In *Intelligent Tutoring Systems*, D. Sleeman and J. S. Brown (eds.). New York: Academic Press.

[Cohen 97] Cohen, A. Near-Field Photolithography. Westinghouse competition paper (unpublished), 1996-1997 (1st prize).

[Csikszentmihalyi 93] Csikszentmihalyi, M. Why we need things. In S. Lubar and W. D. Kingery (eds.), *History from Things.* Washington, DC: Smithsonian Institution Press.

[Druin 87] Building an alternative to the traditional computer terminal. Master's Thesis: MIT Media Lab.

[Eisenberg and Nishioka 94] Eisenberg, M. and Nishioka, A. HyperGami: A Computational System for Creating Decorated Paper Constructions. In *Origami Science and Art (Proceedings of the Second International Meeting of Origami Science and Scientific Origami),* Otsu, Japan, November 1994, pp. 259-268.

[Eisenberg 95] Eisenberg, M. Programmable applications: interpreter meets interface. *SIGCHI Bulletin*, 27:2, pp. 68-83.

[Eisenberg 96] Eisenberg, M. The Thin Glass Line: Designing Interfaces to Algorithms. *Proceedings of CHI 96*, Vancouver, pp. 181-188.

[Eisenberg and Nishioka 97a] Eisenberg, M. and Nishioka, A. Orihedra: Mathematical Sculptures in Paper. *International Journal of Computers for Mathematical Learning.* 1(3): 225-261.

[Eisenberg and Nishioka 97b] Eisenberg, Michael and Nishioka, Ann. Creating Polyhedral Models by Computer.*Journal of Computers in Mathematics and Science Teaching.* 16(4):477-511.

[Eisenberg and Eisenberg 98] Shop Class for the Next Millennium. To appear in the *Journal of Interactive Media in Education.*

[Feiner et al. 93] Feiner, S.; MacIntyre, B.; and Seligmann, D. Knowledge-based Augmented Reality. *Communications of the ACM*, 36:7, pp. 52-62.

[Feynman 85] Feynman, R. *"Surely You're Joking, Mr. Feynman!"* New York: Bantam Books.

[Fischer *et al.* 91] Fischer, G., Lemke, A. C., Mastaglio, T. and Morch, A. The Role of Critiquing in Cooperative Problem Solving. *ACM Transactions on Information Systems,* 9:2, pp. 123-151.

[Flanagan 84] Flanagan, O., Jr. *The Science of the Mind.* Cambridge, MA: MIT Press.

[Galison 92] Galison, P. The Many Faces of Big Science. In *Big Science,* P. Galison and B. Hevly (eds.) Stanford CA: Stanford University Press, pp. 1-17.

[Gilbertson 93] Gilbertson, R. *Muscle Wires Project Book.* Mondo-Tronics.

[Goldstein 89] Goldstein, E. B. *Sensation and Perception.* Pacific Grove, CA: Brooks / Cole.

[Gould 96] Ladders and Cones: Constraining Evolution by Canonical Icons. In *Hidden Histories of Science,* R. Silvers (Ed.). New York Review of Books.

[Halliday and Resnick 62] Halliday, D. and Resnick, R. *Physics, Part II.* New York: John Wiley.

[Kearney 71] Kearney, H. *Science and Change.* New York: McGraw-Hill.

[Lewis 25] Lewis, S. *Arrowsmith.*

[Mandelbrot 88] Mandelbrot, B. *Fractal Geometry of Nature.* New York: W. H. Freeman.

[Mann 97] Mann, S. Wearable Computing: a First Step Toward Personal Imaging. *IEEE Computer*, 30:2, pp. 25-32.

[Miller 84] Miller, A.*Visual Imagery in Scientific Thought*. Cambridge, MA: MIT Press.

[Morgan 88] Morgan, F. *Geometric Measure Theory: A Beginner's Guide.* New York: Academic Press.

[Resnick 93] Resnick, M. Behavior construction kits. *Communications of the ACM,* 36:7, pp. 64-71.

[Resnick *et al.* 96] Resnick, M.; Martin, F.; Sargent, R.; and Silverman, B. Programmable Bricks: Toys to Think With. *IBM Systems Journal*, 35:3, pp. 443-452.

[Shaw 84] Shaw, R. *Dripping Faucet as a Model Chaotic System*. Santa Cruz: Aerial Press.

[Taubes 97] Taubes, G. Beyond the Soapsuds Universe. *Discover* 18:8, p. 52.

[Umaschi 97] Umaschi, M. Soft Toys with Computer Hearts. *Proceedings of CHI '97*, Atlanta, pp. 20-21.

[Zimmerman et al. 95] Zimmerman, T.; Smith, J.; Paradiso, J.; Allport, D; and Gershenfeld, N. Applying Electric Field Sensing to Human-Computer Interfaces. *Proceedings of CHI '95*, Denver, pp. 280-287.

Software

[S1] *Canvas*. Deneba Software. Miami, FL.

[S2] *MacScheme*. Lightship Software. Palo Alto, CA.

[S3] *Photoshop.* Adobe Systems, Inc. Seattle, WA.

Websites

[W1] http://www.cs.colorado.edu/~eisenbea/hypergami/