The Developing Scientist as Craftsperson

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1. Introduction

Increasingly, the day-to-day practice of science education is pervaded by the presence of computational media. Simulations, modelling tools, and virtual laboratories have become the stock in trade of the up-to-date science educator; and consequently the young scientist is a person who, more and more, spends a large proportion of his or her time in abstract and non-physical "worlds". This move toward an increasingly virtualized science education has important benefits for some scientific domains and for some activities: it is arguably only through the simulation of especially complex systems that the student can get a sense of how such systems are capable of behaving. Moreover, the real, physical world constrains us as human beings—and perhaps it constrains our scientific imaginations as well. We cannot easily experience the frictionless environments that would make many principles of Newtonian mechanics more intuitive [White and Horwitz 1987; diSessa 1982]; we do not grasp the behavior of objects moving at speeds near that of light [Horwitz 1994]; we do not see firsthand the evolution of ecosystems, a phenomenon perhaps best understood at a time-scale of millennia [Dawkins 1996]. In all these cases, the building and studying of virtual worlds, of simulations, of abstract models, is plausibly a crucial step in the education of the scientist.

But something is lost, too, in this move away from the physical—something pleasurable, sensually and intellectually, about the behavior of stuff. At our own university, a professor in mechanical engineering lamented to one of us that her students were increasingly arriving at college with no experience of the mechanical world, of real materials. These students, she said, have never actually sat down to fix a bicycle.

Does it matter whether students fix real bicycles, mix real chemicals, collect real butterflies, or view real stars? We believe that it does, and that the advent of powerful and compelling "virtual" environments should now cause science educators to carefully re-examine the delicate relationship between computational media and real-world artifacts. Certainly there are interesting hints about the role of the physical world to be gleaned from the biographies of scientists. Repeatedly, in reading about the childhood or education of famous scientists, one finds that for these individuals the presence of physical objects and the practice of "scientific handicrafts" played an important formative role. The young Stephen Hawking's bedroom has been described as "the magician's lair, the mad professor's laboratory, and the messy teenager's study all rolled into one....On the sideboard stood electrical devices, the uses of which could only be guessed at, and next to those a rack of test-tubes, their contents neglected and discoloured among the general confusion of odd pieces of wire, paper, glue, and metal from half-finished and forgotten projects."[White and Gribbin 1992, p.12]; Linus Pauling learned chemistry as a young assistant in a pharmacy [Csikszentmihalyi 1996, p.86]; Isaac Newton was reported to have tinkered with homemade mechanical devices as a youth[Bernstein 1993, p. 162]. Real-world objects, in the recollections of scientists, often seem to be associated with moments of high motivation or striking imagery. Albert Einstein, in perhaps the most famous anecdote along these lines, distinctly recalled a pivotal childhood experience in which he received a compass as a gift: "That this needle behaved in such a determined way did not at all fit into the nature of events, which could find a place in the unconscious world of concepts (effect connected with direct 'touch'). I can still remember (or at least I believe I can remember) that this experience made a deep and lasting impression upon me. Something deeply hidden had to be behind things." [Bernstein 1993, p.161]. Similar recollections crop up in interviews with other well-known scientists. Richard Feynman, for instance, recalled working with colored floor tiles at a very young age, and likewise mentioned an instance in which viewing a ball rolling in a wagon piqued his early curiosity in the nature of inertia. [Mehra 1994, pp. 3-5] (Feynman also repaired radios and other appliances while still a youngster [Feynman 1985].) The astronomer Fred Hoyle recalled having his interest in science sparked by a chemistry set.[Lightman and Brawer 1990, p. 52] The astrophysicist Margaret Geller, in an interview [Lightman and Brawer 1990, p. 360], recalled working with solid geometric kits as a child, and added "My father is a crystallographer... He had an attraction for any kind of toy that had anything to do with geometry.... For example, I'd make a cube, and he'd explain to me the relationship between that and the structure of table salt. And I'd make an icosahedron, and he'd explain how you see that in the real world.... I would be able to visualize in 3-D. And I realize now—I've talked to lots of people in science—that very few people have that ability."

For those who enjoy the genre of scientific biography, tales like these are easy to find. But maybe, after all, they are just tales and nothing more. Biography, as the more skeptically inclined will point out, is by its very nature anecdotal evidence. And worse—biography isn't even unbiased data. The biographers are writers working for a paycheck; maybe they're looking for easy illustrations of scientific precocity, searching for punchy tales that sound like childhood epiphanies. The scientists themselves, in recollecting their childhood experiences, might be attempting to frame a coherent narrative; perhaps certain events are gilded in retrospect with an exaggerated importance, foreshadowing later developments in much the same fashion as mystical omens do in the biographical essays of Plutarch and Suetonius.

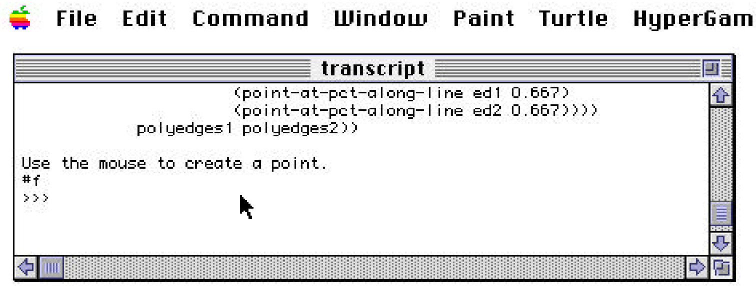
But still... It is hard not to notice the consistent patterns among these histories, cutting as they do across boundaries of time, geography, gender, economic background, and eventual specialization. In all the cases cited—and many more in the literature—the budding interest of the young scientist seems to have been inextricably linked with the day-to-day practice of what might be called a "scientific craft". While individual stories might vary in their credibility, we personally believe in the overall pattern of the biographical data. We'd go so far as to say that many if not most scientists need to encounter objects and experience craftspersonship as students (and quite likely as adult professionals, too). A purely virtualized scientific training, by neglecting this side of human experience, is incomplete and quite probably ineffective.

Of course, we needn't view these two educational paths—one focusing on computational modelling and simulation, and the other on physical objects and handicrafts—as opposites. Indeed, this chapter focuses on an attempt to dissolve some of the apparent tension between the "virtual" and "real-world" paths to learning science and mathematics. We explore a variety of themes that have emerged as salient for us over the last several years in working on a program named *HyperGami*—a system that might be summarized as an educational CAD program for the creation of mathematical paper sculpture. In the course of developing HyperGami, working with the program, and collaborating with HyperGami students of various ages, we have become sensitized to these themes; and we have come to view them as important for science education generally.

In the remaining sections of this chapter we will summarize our work with the HyperGami system, and will use that work to ground our discussion of craftspersonship in science education. The second section of this chapter will present an overview of HyperGami along with the types of constructions that we and our students have made using the system. The third, fourth, and fifth sections will explore the themes that are the true focus of this chapter: (a) the affective and social roles that scientific / mathematical objects (especially homemade objects) are capable of playing in students' lives, (b) the pacing and "rhythm" of students' scientific activities, and (c) the cultures and values associated with different types of physical materials in science / mathematics education. In each of these sections, moreover, we will discuss the ways in which computational media might be used to enhance the benefits of craft activities in science education. In the sixth and final section, we discuss several new directions of our own work and speculate about how computational tools (going well beyond HyperGami) might impact the growth of a craft culture in science education.

2. HyperGami: An Overview

HyperGami is a Macintosh-based software application developed by the authors in the MacScheme programming environment [S1]. We have described the system at great length elsewhere [Eisenberg and Nishioka 1997a, 1997b], and so will present only a summary outline of the application here.



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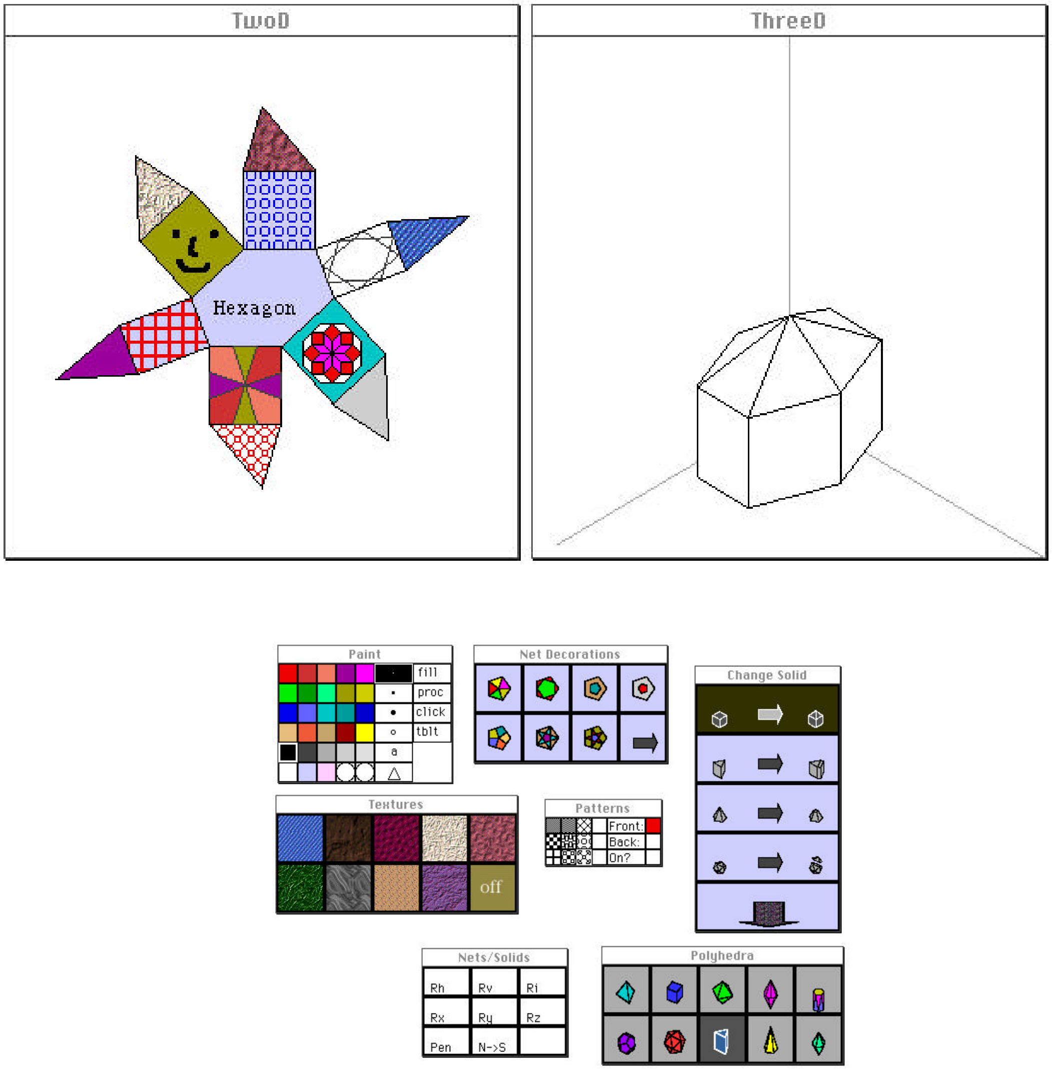


Figure 1: The HyperGami screen in the midst of a sample scenario. The transcript window at top is the interface to the MacScheme interpreter, augmented with a large number of system-specific procedures and data objects. The shape being constructed is shown in a 3D view at right, in the ThreeD window; its unfolded version (or folding net), generated by the system, is shown at left. In the scenario, the user has decorated the folding net using a variety of means—textures, solid colors, patterns, text, hand-drawn and program-created designs.

The basic activity in HyperGami consists of creating novel or complex paper polyhedral models and sculptures; essentially, one creates the three-dimensional shape on the computer screen, allows the software to unfold that shape into a decorable two-dimensional form, and then prints out (and constructs) the eventual model. Figure 1 shows the HyperGami screen in the midst of a sample scenario of just this sort. Here, the user has employed the software to create a particular shape—a stretched, capped hexagonal prism. The shape is visible in the ThreeD window of the screen; the software has also "unfolded" the solid into the folding net form visible in the TwoD window of the screen. The user is now in the midst of decorating the folding net; this can be done by employing solid colors, patterns, textures, hand-drawn decorations, and so forth. Importantly, HyperGami is a *programmable application*, employing an enriched version of the Scheme programming language as part of its interface [Eisenberg 1995]: the user therefore has at her disposal a complete Scheme interpreter, augmented with an extensive (and always growing) library of procedures and objects for creating and decorating HyperGami constructions. To take an especially simple corollary of this idea, in the Figure 1 scenario the user has employed HyperGami's turtle procedures to decorate one of the faces of her hexagonal prism with a geometric design in the spirit of Abelson and diSessa [1980].

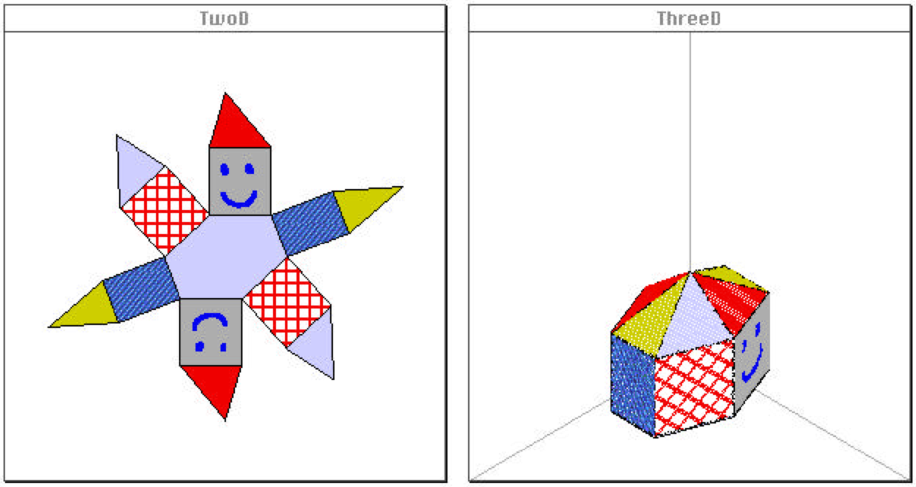


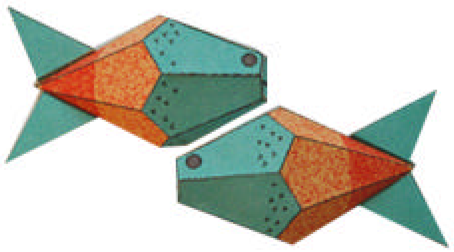
Figure 2: The user has transferred the decoration from the folding net at left to the three-dimensional view at right. The transfer takes place on a pixel-by-pixel basis, which makes it somewhat slow and laborious (not to mention inexact), but the view at right does give a reasonable preview of what the eventual folded shape will look like.

There are many more features in the HyperGami system, but space precludes a more thorough discussion. Several points do deserve mention here, however, as they will reoccur in later discussion within this chapter. First, HyperGami includes tools through which the user may transfer a decoration from the folding net to the three-dimensional view of a polyhedral object; this permits the user to predict, in some measure, what the eventual construction will look like if the current folding net is printed out and folded into three-dimensional form. Figure 2 shows an example: here, the decoration from a hexagonal prism such as that shown in Figure 1 has been transferred to its three-dimensional rendering.

A second point is simply that paper—the basic material of HyperGami constructions–is itself an extremely rich craft medium, and one whose versatility is still expanding. HyperGami creations may be printed out on standard printer paper, on glossy paper, on thick cardstock, on pre-tinted papers, on acetate, on large poster-sized sheets. (We ourselves have barely begun to explore the varieties of available paper available, and to experiment with these papers in our constructions.)

A third point is that HyperGami includes a number of features specifically designed with the needs and problems of the paper crafter in mind. For instance, the program includes tools with which the more advanced user can "tailor" a folding net in such a way that it is easier to fold (or perhaps to decorate). Many of the built-in procedures for decorating folding nets take advantage of the geometric properties of the net's polygons (e.g., one of the example procedures provided with the program permits the user to decorate a net polygon with "spokes" radiating from the center of the polygon to each of its vertices). Recent additions to the program permit the user to generate "tabs" on the folding nets (these greatly assist in the construction of the eventual shape) and a "surface turtle" package that allows the user to move a Logo-style turtle over the entire surface of a polyhedron, "jumping" smoothly from face to face of the net as suggested by the discussion in Abelson and diSessa [1980, ch. 6].

Figures 3-9 illustrate the types of constructions that we and our students have created in HyperGami. Figures 3 and 4 depict polyhedral sculptures ("orihedra") that we have created; the figure at left depicts two fish (created from trapezohedra and prisms; the figure at right depicts two twins ("Tweedledee- and Tweedledum-ahedra") built from a variety of shapes including the icosidodecahedron (the bodies of the figures) and the small rhombicosidodecahedron (their heads).



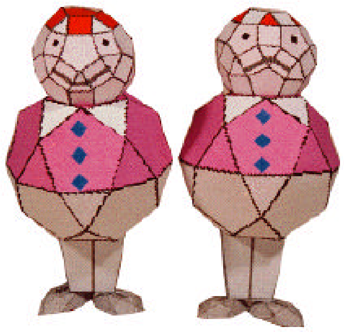
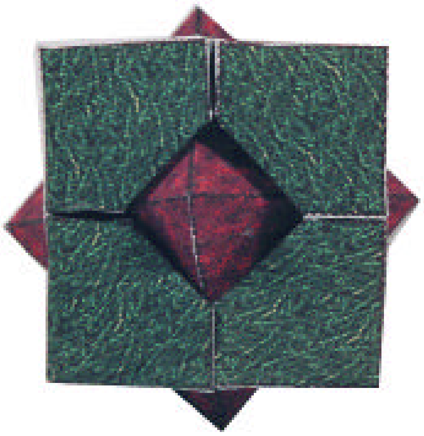


Figure 3 (left): A polyhedral sculpture of a pair of fish.
Figure 4 (right): "Tweedledeeahedron and Tweedledumahedron."

Figures 5 and 6 depict work done by HyperGami students. Since the development of HyperGami first began, we have worked with over fifty students ranging in age from elementary to high school. Typically, these students work with us as individuals or in pairs or small groups, for a period of an hour or two per week over the course of about a semester. ([Eisenberg and Nishioka 1997a] and [Eisenberg and Nishioka 1997b] include more detail on our experiences with students.) By and large, students work toward creative projects of their own devising such as the sculptures in Figures 5 and 6, although over the past year we have also begun the creation of more specifically curricular materials (such as exercises), mostly for use with our high school-aged students. Figure 5 shows a marvelous polyhedral figure—a "trapped octahedron"—in which an octahedron is shown embedded within eight pieces that collectively make up a figure rather like a surrounding cube (this piece was created by a sixth grade boy). Figure 6 shows a polyhedral sculpture, composed mainly of prisms and pyramids, of a kangaroo (the body is a truncated tetrahedron) done by a twelfth grade girl.



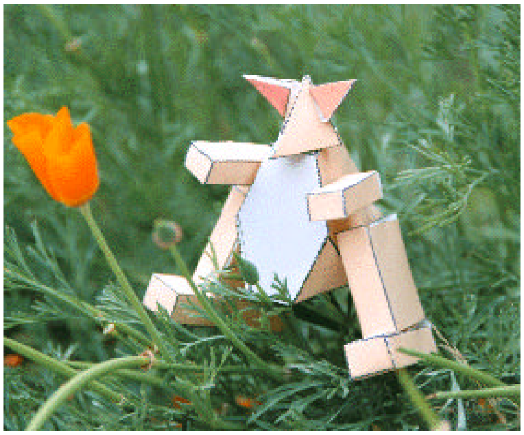


Figure 5 (left): A "trapped octahedron" polyhedral construction by a twelve-year-old boy.
Figure 6 (right): A polyhedral kangaroo designed and created by a high school senior.

Finally, Figures 7, 8, and 9 depict work done in materials other than paper. Figure 7 shows a pair of "pillowhedra" created by printing out folding nets onto special paper which can then transfer its decoration to fabric; usually, this process is employed to create customized T-shirts, but it can just as easily create three-dimensional sculptures in fabric. Figure 8 shows a rhombic dodecahedron created from soap (using a HyperGami construction as a mold), and Figure 9 a polyhedral wax candle (created in similar fashion). These last examples are shown merely to illustrate the ways in which an application such as HyperGami can lead to the construction of an immense variety of craft objects in different media.

Figure 7 (left): Two "pillowhedra" made from sewn fabric.
Figure 8 (center): A rhombic dodecahedron of soap.
Figure 9 (right): A truncated pyramid of wax, decorated with a turtle-graphics design.

3. Theme 1: The affective role of objects in science education

In the previous section, we introduced HyperGami and presented an illustrative range of artifacts that our students and we have created with the program. As mathematical objects, HyperGami sculptures fit within a longstanding tradition of polyhedral modelling in mathematics education (see, for instance, [Cundy and Rollett 1951; Hilton and Pedersen 1994; Jenkins and Wild 1985]). Indeed, the autobiographical anecdote told by Margaret Geller, and recounted earlier, suggests a role for such objects as effective practice materials in developing skills of spatial cognition.

For the purposes of this chapter, however, we would prefer to take a broader view: rather than focusing on the (relatively narrow) mathematical issues raised by polyhedral modelling alone, we wish to explore the more important and general role of computationally-enriched craft activities in mathematics and science education. These issues go well beyond the specific examples of HyperGami work—they include many other types of materials besides paper, and other paradigms for computational media besides stand-alone applications. Nonetheless, our own experiences with HyperGami are what made these broader issues accessible to us; and as a result, we will tend to use our HyperGami work as a source of illustrations.

3.1 Crafts and affect

For us, one of the crucial aspects of our (and our students') HyperGami experience is that it has over time produced objects that we now enjoy having around. That's a simple observation, and at first blush it might seem almost trivial—why should mathematics or science educators concern themselves with the creation of fun objects? The answer is suggested by the quotes from and about young scientists mentioned earlier: Geller's polyhedral models, Feynman's geometric tiles, Newton's gadgets, all seemed to provide a sensual as well as intellectual pleasure. And even more: pleasurable physical objects contribute to a setting, a sense of place, in which mathematics and science may be studied. Recall, for instance, Hawking's room: it was (as described) a rich, full setting in which a young scientist could be stimulated on a day-to-day basis.

How different this is from the physical environment of science education as it is increasingly defined by computational media! No matter how aesthetically pleasing the view from a computer screen may be, that view is after all only a tiny and temporary fraction of one's setting. As computer scientists, we know this phenomenon well: month after month, year after year, as we toil away at our computers, we return to our offices and see no tangible change to reflect our work back to us. A computer whose disk has been filled with our programs and papers looks very much like the computer on the day we purchased it. Perhaps this is why so many computer scientists' offices are decorated with screen dumps of their work: no doubt, the screen dumps are useful for a variety of reasons, but perhaps their most important role is emotional. The screen dumps on the wall tell the programmer that he or she is, at the end of the day, producing something—that progress is being made. In some small measure, the screen dumps cheer us up.

Unfortunately the measure of cheer provided by such means remains small. When science and math education are centered in purely virtual media, they foster relatively uninspiring physical surroundings: they provide students with rooms, laboratories, and corridors unenlivened by the students' own work and creations. And for many of us—perhaps most of us—setting matters. Csikszentmihalyi *et al.* [1993], in their provocative study of talented high school students, note that students who work within the arts tend to have an easier time being motivated academically than those who study math and science. Part of this motivation is provided by the studio setting in which the artists work:

> "[G]ifted young artists mostly work in a studio class at school. There they work by themselves but are surrounded by peers engaged in similar activities. The drawing or sculpture of one student is accessible to the others and therefore can be shared as it progresses. The work itself can perhaps best be characterized as an *expressive performance*...." [p. 105; italics in the original]

For students of science and (perhaps more pointedly) mathematics, even the most successful and enjoyable work often leaves no souvenirs, no reminders, no physical traces at all. To some extent this is just the way these fields operate—solving a mathematical problem is an abstract activity whose purpose is to leave us intellectually, not materially, enriched. But this culture of asceticism can over time produce an unnecessary emotional strain. This may account for the sense of longing that occurs in the students described by Pedersen [1988] as they encounter the polyhedral models in her office: "I have these models in my office and students come in and beg to know how to make them. They never ask, 'What are they good for?' They know! And we know too."

Craft objects not only visually enrich the physical environment of the young mathematician and scientist, but they do so in a way that reflects the personal experience and progress of the students. In this sense, they take on biographical meaning that (say) a poster or store-bought object cannot. In the same vein, a craft object can play a role as a personal statement, or public display, or gift. Repeatedly we have seen our students put their HyperGami objects to just such uses—polyhedral models and sculptures are given as presents, used as Christmas ornaments, placed on display in the home or classroom. One student modelled her pet rooster in polyhedral form; another gave a nickname to her favorite polyhedron. We ourselves have used HyperGami models as thank-you notes, wedding and birthday gifts, and souvenirs of special occasions. In this way, HyperGami objects (and craft objects more generally) take on a versatile role as "social currency"; and it is precisely along these day-to-day social dimensions that math and science education are typically so impoverished.

There is yet another, more intellectual role at which tangible objects excel: they symbolize and reflect a growth in skill over time. When a student creates and displays objects over the course of a semester, or year, or period of several years, the display itself becomes a tangible reminder of the student's growing skills. Perhaps last year's mathematical mementoes are much simpler (or less polished) than this year's; perhaps last year's mechanical or electronic projects are less impressive; perhaps the student has become more adept at producing homemade scientific instruments. The crucial point here is that, in comparison, the purely computational world offers little in the way of a continuous, unconsciously available record of progress: of course a student can bring up a sequence of programs or simulations that he or she has written, but the act of bringing up that sequence is deliberate and tedious. There is little in the virtual world that is analogous to the simple process of viewing, without even meaning to, a shelf full of ever-improving craft objects.

Creating mathematical and scientific objects via handicrafts is an emotionally satisfying activity with an intellectual message: it serves to demystify the practice of math and science as a profession. A student who has created her own scientific instrumentation at home is just a little less likely to regard the laboratory as a place of dread; a student who builds mathematical polyhedra in the classroom will be less likely to flinch when he encounters those solids in a later course in chemistry or solid geometry; a student who has built, and held, mechanical models in the garage has a sense not only of the principles but of the gritty aesthetics of engineering—the way materials bend, or heat with friction, or hold up with time, or smell when they are new. For these students/craftspeople, the scientific world is simply an outgrowth of their most homey, day-to-day activities.

3.2 Computation and the affective role of crafts

How can the addition of computational media enhance the positive affective nature of scientific craftwork? There are two major answers to this question, suggested by our experiences with HyperGami. First, by making the craftwork more personalized and expressive, computational media can push scientific crafts toward an activity that might more appropriately be called "scientific artwork." In the case of HyperGami, students—rather than simply building polyhedral models—are able to use the software to make objects with personal meaning (a dinosaur, a holiday Christmas tree, the aforementioned pet rooster). More generally, computational media allow us to rethink scientific crafts along new lines. An experiment with geometric optics can become (under the influence of the appropriate computational tool) a means for constructing artistic effects with light; a kit for building mechanical demonstrations could become a system for creating whimsical automata; a crystal-growing kit could become part of a larger application in which students design (on the computer screen) and then construct sculptures or tangible landscapes containing mineral forms.

A second answer to the question of how computation can enhance the affective role of crafts focuses on the notion of displaying or sharing objects.

As we have mentioned, craft objects tend to be put on display, or given as gifts; in either case they are created in the anticipation of an audience other than their creator alone. Computational tools allow for craft objects to be shared, displayed, or documented in more powerful and inventive ways than were heretofore possible. In the case of HyperGami, students' works have been displayed on the World Wide Web, giving those works an effectively huge potential audience; we ourselves have placed folding nets on the Web so that one of our sculptures could be recreated by visitors to the HyperGami website. The fact that HyperGami figures are created in a medium that is originally computational allows those figures to be duplicated, annotated, and altered in ways that would have been otherwise difficult; for instance, it would be a relatively trivial matter to recreate the polyhedral fish sculptures of Figure 3 at (say) a larger scale by simply printing out the folding nets at a larger magnification. In the same vein, someone who wishes to recreate one of our sculptures with a different pattern of decoration would have little trouble simply taking the original (undecorated) folding nets and altering them; indeed, several of our younger students' projects have been of precisely this type.

4. Theme 2: Crafts and the pace of science education

Working with craft materials takes time—often, a lot of time. While a simple HyperGami project can generally be completed in an hour or two, a moderately complex project may easily stretch out over several evenings of construction. And of course, HyperGami is not especially unusual among craft activities in this respect—all sorts of crafts, from the creation of mosaics and stained-glass windows to the carving of wood, can at times be similarly slow-paced.

Is slow pace a problem? Set against the rhetoric of most educational research, it might seem so. Educational researchers—especially those in educational technology—often measure the success of a program by how much less time the students need to spend on learning some material than they did previously (e.g., one might see a claim that, because they used a particular application, students were able to pass a standardized algebra test in a third less time than they previously required). This is an impressive result, assuming that the study time is itself devoid of pleasure. If we are doing something distasteful but necessary, we certainly wish to accomplish the task in less time.

Perhaps, though, the success of science and math education should not be measured in terms of how fast we can get the ordeal over with. While that metric may be appropriate for some training situations—e.g., when we need to acquire some specific skill in order to move on to more interesting work—it seems a joyless metric to apply to the educational enterprise as a whole. We might rather view the success of science and math education in terms of how much structure it is capable of bestowing on the student's leisure hours. A student who turns her room into a lab, or his garage into a workshop, or who looks forward to returning to her telescope at night, or who mulls over a mathematical puzzle on the bus, or who ponders a scientific question during a morning shower, is one who has experienced a good scientific education. In contrast, a student who passes his tests in half the time and looks forward to spending that extra time in front of the television set is a problematic success story at best.

4.1 Scientific crafts and the rhythm of science education

Alfred North Whitehead, in his book *The Aims of Education*[1929], discusses the notion of a "rhythm" to the educational process:

> Life is essentially periodic. It comprises daily periods, with their alternations of work and play, of activity and of sleep, and seasonal periods, which dictate our terms and our holidays.... These are the gross obvious periods which no one can overlook. There are also subtler periods of mental growth, with their cyclic recurrences, yet always different as we pass from cycle to cycle, though the subordinate stages are reproduced in each cycle. That is why I have chosen the term 'rhythmic,' as meaning essentially the conveyance of difference within a framework of repetition. Lack of attention to the rhythm and character of mental growth is a main source of wooden futility in education.[p. 29]

When technology is applied to science and math education, the rhythmic patterns that Whitehead describes seem, too often, to go unacknowledged. The pacing and style of many applications are reminiscent of arcade games—a mixture of constant animation, sound, and bright colors. Sometimes, of course, that sort of pace is exactly what a student might wish (we ourselves enjoy video games as much as the next person), but a relentless focus on one sort of pacing for science education leaves the student inexperienced in and uncomfortable with the slower, dreamier side of impassioned work.

We view the leisurely pace of craft activities within science education as a largely (though not uniformly) positive feature. True, a slower activity demands a longer attention span of the student; but it also rewards that longer attention span, and may thus serve over time to extend it. It distresses us to hear educational innovators simply assume that students cannot or will not concentrate—that their short attention spans are a fait accompli, to be accommodated but not challenged by their tools. In our view, students' reflexive (and counterproductive) expectation of video-game pacing is a predictable and inevitable result of a culture of design that refuses to challenge itself.

Allowing for the pace of craft activities to invade science and math education is not, in other words, simply a challenge to the students' expectations; it is also a challenge to those of the designers and educators, to the educational culture. Often, the real goal of a craft activity is simply to spend extended time in the contemplation of the activity itself, getting the feel of the material into one's hands and seeing a construction take shape over time. One would no more seek to compress the time period of this activity than to compress a performance of "Clair de Lune" into thirty seconds. And it is a healthy exercise—again in our view—for educators to assume that students will and should have periods of meditative time on their hands. Maybe that assumption is a bit of a fiction, but we think it's a fiction that over time can become a self-fulfilling prophecy.

The longevity—or at least the potential longevity—of craft objects is still another factor that deserves mention in this context. Craft objects, as suggested by the discussion in the previous section, have educational value that may be played out over a span of months or years. A HyperGami polyhedron on the shelf may, months later, suggest a starting point for a sculpture; or the student may suddenly notice a pattern in the shape that escaped her attention at the time the object was created. A craft object created by a fifth-grader in September, and displayed in a classroom, might be the subject of a discussion with its creator in April; again, it is unusual for the products of classroom activity (like workbook pages) to have any meaning or resonance for their creators more than a day or two after completion.

4.2 Computation and the pacing of scientific craft activities

Computational media offer an important element in regulating the pacing of craft activities: namely, they allow for a surer sense of direction and eventual success in the creation of a craft object. In our own experiences with HyperGami, we have noticed something that we have informally called the "it's-going-to-be-so-cool effect"—the phenomenon where, having begun the creation of a particular model, we can see that it is turning out well. When the "cool effect" takes hold in the midst of a construction project, it can prompt us to keep working for hours, just to see the final product.

Computational media can extend the "cool effect" of craftwork by giving the creator a relatively early view of what the finished product will (or might) be. In the case of HyperGami, the software enables the user to see a view of what the eventual decorated three-dimensional shape will look like; sometimes it is precisely this view that enables us to know that a shape is worth creating. In the absence of this sort of predictive power of computational design media, the craftsperson needs to proceed on a greater dose of faith in the eventual product; and he may suffer intense disappointment when the result of hours of work is a product whose imperfections could have been apparent at the outset if presented by the appropriate design tool. These elements—faith, patience, and occasional disappointment—are arguably necessary elements of the crafting process. Nonetheless, having a computational tool that permits us to make sounder judgments about the eventual success of a crafting project might allow the novice a less frustrating introduction to the process of crafting itself. Moreover, if well designed, such a tool should not entirely eliminate the element of risk (and those associated elements of faith, patience, and disappointment) that accompany crafting; rather, the tool should ideally enable the expert crafter to raise his ambitions a bit higher.

5. Theme 3: Materials as representatives of specific cultures

5.1 How should we think about scientific craft materials?

Once we start attending to craft activities in science education, an astonishing variety of ways of interpreting materials, of understanding them, begins to be revealed. Materials—whether paper, Lego bricks [P2], FischerTechnik kits [P1], wooden blocks, modelling clay, yarn, balsa wood, stained glass, fabric, or myriads of others—are associated with their own particular cultures of usage. While these cultures are rarely made explicit in discussions of scientific education, they seem to operate forcefully in the lives of students. Some types of materials (e.g., wooden blocks) will be seen as appropriate for certain ages of children, but not for others: a first grade classroom will supply at least some different materials from a sixth grade classroom. Some materials (e.g., construction sets) might be marketed primarily to boys; others (e.g., glass beads) to girls.

One could devote volumes to a fine-grained critical analysis of the cultural implications of different craft materials; but we also believe that it is important not to make too much of this sort of analysis, which can easily become a dry academic exercise. After all, a notion such as "the implicit culture of a material" is only an approximation. Some adults play with wooden blocks; some children work with oil paints; some little girls play with Lego bricks, and some little boys with fabric. Still, it is worthwhile to explore these issues, if only to alert ourselves to potentially novel and productive ways of thinking about the design of scientific craft activities.

Our own experiences with HyperGami have suggested to us a number of dimensions along which to think about craft materials in science and mathematics education. These dimensions are not orthogonal—the placement of a certain material along one dimension will likely impact its placement along at least several others. But, for us at any rate, these dimensions offer some conceptual purchase on how to think about the overall landscape of scientific crafts.

- Longevity / Permanence

While some craft materials are especially short-lived (perhaps the most obvious examples would be edible craft materials, such as chocolate), others (like hardwood or ceramics) are meant to last. Materials such as candle wax, or the paper of HyperGami constructions, occupy an interesting middle ground—while paper polyhedra are hardly likely to last for decades, they can easily last for months or years (we now have several early constructions that are over four years old). In some cases, additional steps may be taken to make materials last longer (for instance, we have recently begun spraying HyperGami constructions with various fixatives to prevent the colors from fading over time). Longevity is an interesting dimension in the design of scientific craft materials, since arguably those materials that can last for at least a half-year or so are capable of longer-term educational effects; ephemeral constructions (e.g., the results of chemical experiments) may well be have educational impact, but the creative designer of scientific crafts may think about ways of extending the longevity of such constructions (in the case of chemical experiments, for instance, the designer might consider allowing certain chemistry-kit experiments to include slow reactions that take place over a period of months).

- Reparability (undoability / redoability)

Some craft materials are designed so that constructions may be taken apart after a time. Many commercial modular materials—Lego blocks [P2] , Polydrons [P3], Zometool kits [P4], to name just a few—have this property: once a project has been completed, it can be decomposed and its parts reused in some other project. Other craft materials—clay, paper, wood—are less likely to be used in creating "undoable" projects (a HyperGami piece, for instance, is meant to be folded once and for all). Reparability is an advantage in some ways—it means, after all, that unpromising projects can be stopped midway, or that simpler projects can be used to supply parts for later ones. But reparability has interesting consequences, not always helpful, in other directions. For one thing, "undoable" objects are, in a sense, impermanent (to recall the previous dimension), even if they are made of sturdy materials: a Lego construction is unlikely to last very long even if its individual pieces do. Undoable objects seem to have less emotional investment, less power as "social currency", perhaps because of their very impermanence or the possibility of reuse: one is unlikely to give a Zometool construction as a gift, in part because one might need the pieces of which it was made later on. In any event, the reparability or undoability of craft materials implies interesting consequences for the uses of those materials.

- Affordability

This is an obvious dimension to consider in thinking about educational crafts. Typically, when one thinks about "cheap" craft materials, the standard examples are things such as yarn, paper, water-based paints, and so forth. It is worth mentioning, though, that a large variety of newer, more specialized craft materials—suitable for science-education projects—are in fact relatively affordable: "smart" materials (such as "muscle wire"[Gilbertson 1993]), diffraction gratings, flexible mylar mirrors, temperature-sensitive films, glow-in-the-dark paints, and so forth. (We have, in other writing, referred to such materials as "middle tech", somewhere on the spectrum between the obvious "high tech" examples of digital logic and the "low tech" examples of clay and yarn. [Eisenberg and Eisenberg 1998b]) While affordability is clearly desirable in a scientific craft material, then, it is also a dimension along which a material's classification need not be forever fixed: after all, many of today's most commonplace materials (paper among them) were at one time rare and precious.

- Intended audience

Craft materials often seem designed with a particular audience in mind, at least within some particular surrounding culture. For example, the colors with which materials are made might suggest that they are intended for young children (bright primary colors), or for a predominantly female or male audience; or the fact that materials require fine motor control might suggest that they are intended for older students; or perhaps the fact that materials (e.g., in chemistry sets) have certain physical risks associated with them suggests that those materials are intended only for adults, or at least for students who have adult supervision. In our own experiences with HyperGami, we have noticed a general, age-related response to the medium of polyhedral paper sculpture: while adults and young children have often expressed delight, teenagers (especially males) have often been noticeably cooler. [Eisenberg and DiBiase 1996] This in turn has led us to rethink the types of examples that we now present to high school students—these examples now tend to de-emphasize the element of whimsy that, to teenagers, can seem perilously undignified.

There are still other dimensions that could be mentioned in a more thorough discussion of this kind: the portability of craft materials; their associated settings or infrastructure; or the affordances that some materials might offer for collaborative work. Nonetheless, the four dimensions presented above at least suggest the lines of thought that our work with HyperGami has opened for us. These, of course, are dimensions that apply equally well to traditional and computationally-enriched craft materials; but in the following paragraphs we discuss some specifically new dimensions that are introduced by the advent of computation into scientific crafts.

5.2 Computation and New Ways of Thinking About Crafts

- Role of computation in design

HyperGami, as an application, offers a clear illustration of one style of computationally-enriched craft: in this style of work, the craftsperson does most of the explicit design work on the computer, and then completes the construction using real-world materials. This paradigm, we believe, could profitably be extended toward other sorts of scientific craft activities—geometric optics projects, crystal-growing sets, kaleidoscope design, to name just a few. In any of these cases, one could well imagine beautiful software applications whose express purpose is to assist the student of science in creating and understanding real-world objects; and, like HyperGami, these applications could presumably expand the range of expressiveness or complexity of the craft, helping the designer create never-before-possible objects.

This is not, of course, the only way by which computational media can affect the design of craft objects. A software application might, for example, only be used to design part of some larger project (e.g., an application might be used to decorate but not design balsa wood gliders); or an application might be used mainly to provide more elaborate or animated instructions on how to do the crafting itself (e.g., there exist CD-ROMs for teaching origami and paper airplane construction). Conceivably, software might be used in an expanded role, beyond that illustrated by HyperGami: for instance, an application might be designed to assist the craftsperson not only in the design phase, but during the process of physical construction itself. (For instance, one could imagine an application that assists students in constructing a terrarium and then later assists them in monitoring or analyzing the miniature ecosystem that they have created.)

- Craft objects with embedded computation

In most of the discussion thus far, we have assumed rather traditional views of computation and crafts as individual entities: i.e., "computation" is provided by a large machine sitting on the desk (and probably connected to other large machines via networks), while "crafts" are traditional physical materials. An especially interesting direction for integrating computational media and crafts is to embed a certain degree of computation within the craft materials themselves. This is, of course, the direction pursued creatively by Resnick and his colleagues at the MIT Media Lab in developing the "programmable Lego brick" and its conceptual offspring [Resnick 1993, Resnick *et al.* 1996]; likewise the now-popular idea of "wearable computing" offers fascinating possibilities for integrating computational media and fabrics. [Mann 1997]

There are still other possibilities for integrating computation and crafts—especially those crafts that show up often in science education. One might envision, for instance, a set of plastic biological models (such as those of the human heart or eye used in classrooms) augmented with computational elements so that students can observe (e.g.) phenomena such as arrhythmia. Or the simple frameworks constructed for use with soap films (so that students can observe minimal surfaces generated by the films) might be made so that the frameworks shift or twist slightly after construction, revealing the ways in which minimal surfaces readjust under dynamic conditions.

Often, "embedded computation" within craft objects implies adding some sort of dynamic (as opposed to static) element, as in the two examples above. But this needn't always be the case: computational elements might simply be used for measuring, monitoring, or communicating. A homemade water-based barometer, for instance, might be equipped with computational elements that signal (e.g.) an approaching storm or that simply record readings of water levels over a period of time for the purpose of later display. A homemade mobile might include a computational device whose purpose is to record and graph the movements of the mobile's arms over the course of a day.

The advent of small, light, flexible computational devices provides an endlessly fertile ground for experimenting with the integration of computers and crafts in novel ways. Indeed, we and our colleagues and students have used the MIT Media Lab's "cricket"—a recent, smaller and lighter version of the original programmable brick—in a wide variety of science-related projects (including a "computationally enriched kaleidoscope" by A. Warmack, a cricket-driven dynamic color display by M. Burin, K. Johnston, and D. Olvera employing tanks filled with water tinted in various shades, and a cricket-operated magnetic field sensor devised by T. Wrensch). [Eisenberg and Eisenberg 1998b] By thumbing through any catalog of scientific toys and crafts, or by strolling through the local science museum, one is sure to arrive at new ideas for the uses of embedded computation within traditional scientific crafts.

- Programmability/reprogrammability/ adaptability

One final, and important, dimension worth noting in this discussion is that of programmability. Some examples of computational craftwork might employ computers as part of (e.g.) clothing, to change color in different lighting conditions; but the behavior of the object under consideration is fixed by the designer and is not alterable by the user. In other cases, the user might be able to program the behavior of the object at some initial point (for instance, the user might specify the behavior of a programmable mobile or kaleidoscope), but could not alter the program thereafter; or perhaps the user could reprogram the computational element in some restricted fashion, but could not alter it while it was running within the constructed device. A more powerful possibility would be to allow the user to reprogram the computational elements of some craft object on the fly, while the device is running; this would permit (e.g.) a user to reprogram or fine-tune a programmable barometer while it was in the process of taking measurements. Finally, one might allow for the possibility of a certain level of internal adaptability in the device's programming, based perhaps on its use; for instance, a computer-augmented home-built Van de Graaff generator might be constructed so as to permit higher-voltage demonstrations only after it has been successfully used in a certain number of (relatively safer) lower-voltage experiments.

6. New directions in computational crafts

Over the last several years, we have come to derive such pleasure from integrating computation and papercrafts that it is often difficult for us to select, like sage adults, among the myriad lines of thought and work to pursue. Certainly there is much more development that we plan for HyperGami itself. Recent additions to the program (besides a couple mentioned earlier in this chapter) include the implementation of loadable texture libraries, several new geometric operations on solids, and the (still experimental) development of "intelligent spatial advisors" to assist users in choosing possible customizations to perform on polyhedra.[Eisenberg and Eisenberg 1998c] In the somewhat longer term, we have begun a reimplementation of (much of) HyperGami in Java, which we hope will permit both a much wider dissemination and evaluation of the program. And there are numerous additional research issues that we fervently wish to pursue within the narrow context of HyperGami development—representing the bending (and perhaps crumpling) of paper surfaces, representing additional paper-sculpture techniques (such as tearing or cutting slits in surfaces), representing sets of distinct polyhedra on the screen at one time (in the current version of HyperGami, each individual polyhedron must be constructed separately, and one does not typically view sets of polyhedra on the screen at one time).

Going beyond the specific domain of HyperGami, there is still much to do within the basic paradigm of the original program—i.e., creating software applications to assist in the design of more complex or expressive scientific crafts. One might imagine (just to take a few examples) an application to aid in the design of metal-ring topological puzzles; or an application for the design of marionettes; or an application to assist in the practice of creative glassblowing; or an application for the design of new types of birdhouses; or for the design of novel sorts of kites. Perhaps some of these ideas would fare better than others in practice, but there is a single notion behind them that is consistently worth exploring—namely, that computational media (especially when augmented by a composable notation like a programming language) can enrich those activities which young scientists have historically found to be motivating and pleasurable.

There are other directions to pursue that move beyond the basic paradigm of HyperGami-like applications. In the previous section we alluded to new possibilities for integrating computational elements within craft objects themselves (along with a few primitive illustrations of the idea). We believe that many of the smaller, more ubiquitous pieces of scientific crafts—mirrors, motors, springs—might well be designed to include small amounts of embedded computation (e.g., one might imagine a simple "intelligent spring" that sends a signal if it is stretched beyond the limit at which it is well approximated by Hooke's law). And there are natural ways in which the World Wide Web could augment the practice of crafts: for instance, it is quite plausible to imagine a world in which scientific craft objects routinely come with their own associated websites explaining how those objects were constructed. (Several ideas along these lines are mentioned in [Eisenberg and Eisenberg 1998a].)

Even more ambitiously, it might just be possible to change the fundamental mindset with which craft objects are created. Traditionally, craft materials are not designed with educational purposes in mind: the early manufacturers of paper almost certainly never envisioned the development of mathematical papercrafts, and the first makers of soap probably never thought about the use of their invention for the study of minimal surfaces. In other words, the traditional relationship between the development of materials and the needs of science educators has been serendipitous—industry creates, and (on occasion) the world of scientific crafts catches a lucky break. Perhaps we can do better by starting from a perceived need in science education, and attempting to design real-world crafts in response. Indeed—returning to the examples with which we began this chapter—it may not be hopeless to design new craft activities or craft materials (perhaps with some sort of embedded computation) that illuminate concepts such as Newtonian mechanics in the absence of friction, or wave/particle duality, or objects moving near the speed of light, or evolutionary processes that typically take place over millennia. The real world, the world of crafts, is partly our own creation as designers; and the basic stuff of home science can itself be a target domain for innovation.

For us, these (admittedly futuristic) notions have originated with paper. In designing, using, and teaching with HyperGami, we have come to feel that this system is most fruitful as an "object to think with"—a single instance of a much larger class of examples in which computers and traditional (or non-traditional) craft materials are woven together. There is something satisfying about using new technology to work within a tradition of paper geometric construction that dates back at least to Albrecht Dürer in the sixteenth century. [Malkevitch 1988] And there is something satisfying in the varied pace of the HyperGami activity itself, in which abstract design on the computer screen is followed by patient and careful handling of paper in all its exquisitely tangible manifestations.

After all, it's a natural desire to employ all one's senses and cognitive powers in the course of a single project. We do not feel that a love of crafts is incompatible with technophilia, nor that an enjoyment of computer applications must detract from time spent in crafting. The world is not, or should not be at any rate, a battleground between the real and the virtual. It is instead a marvelous continuum, a source of wonders that blend and knead together the natural and artificial, the traditional and novel, the scientifically objective and the personally expressive, the tangible and the abstract. We anticipate a future in which ever more astonishing things will present themselves to our minds, and ever more astonishing ideas to our hands.

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