

Mindstuff: Educational Technology Beyond the Computer

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Abstract. Seymour Papert’s book *Mindstorms*, first published in 1980, has had a profound impact on the ideas (and lives) of a generation of educational technologists and designers. This paper re-examines several of the most compelling ideas from *Mindstorms* in the light of recent advances that blend computational technology and materials science. In some respects, this growing détente between the physical and virtual lends greater force to Papert’s ideas than did the original examples in the book, centered as those ideas were on the then-current portrait of the desktop computer.

1. Introduction: Children, Materials, and Powerful Ideas

“Before I was two years old I had developed an intense involvement with automobiles. The names of car parts made up a very substantial portion of my vocabulary: I was particularly proud of knowing about the parts of the transmission system, the gearbox, and most especially the differential. It was, of course, many years later before I understood how gears work; but once I did, playing with gears became a favorite pastime.... A modern-day Montessori might propose, if convinced by my story, to create a gear set for children. Thus every child might have the experience I had. But to hope for this would be to miss the essence of the story. *I fell in love with the gears.*” [*Mindstorms*, pp. vi-viii; emphasis in the original]

Seymour Papert’s book *Mindstorms*¹—the source of the quote above—was originally published in 1980. It may be unfamiliar to some readers, especially those too young to remember its publication. But for many people of my generation—especially those interested in education and computers—the book played a role rather like that of the gears within Papert’s own life history. That is to say, we fell in love with *Mindstorms*; and the book’s central themes have, over time, become catchphrases in our minds—“powerful ideas”, “microworlds”, “mathetic principles”, “procedural knowledge”, and so forth. Indeed—to take yet another marvelous turn of phrase from the book—these notions have become “objects-to-think-with” in our own lives.

The overriding idea behind the book is the (potentially) powerful role that computers might play in the intellectual and emotional lives of children. Immediately following the passage quoted above, Papert continues:

My thesis could be summarized as: What the gears cannot do the computer might. The computer is the Proteus of machines. Its essence is its universality, its power to simulate. [p. viii]

This paper is an extended reflection on the central thesis of *Mindstorms* in the light of how notions such as “computation” and “technology” have evolved in the twenty-three years since the book was published. Briefly, my argument is that the central themes of *Mindstorms* retain their power, importance, and fertility; but they do so in ways that extend, and occasionally run counter to, the original examples and images from the book. For the portrait of “the computer” that is implicit within, and central to, the vision of *Mindstorms* has over time developed into something far less monolithic and much more truly Protean than could have been explained (or perhaps even imagined) in 1980.

That word “Protean” is a good place to start. It must be noted that in some important respects, the computer—at least the “classical” notion of the personal computer, as a desktop machine—is one of the *least* Protean of artifacts in our lives. After all, recall what the god Proteus could do: he could change shape. Or—to put the matter even a bit more generously—he might look different this afternoon than he looked in the morning. Consider, in contrast, how *little* one’s desktop computer changes, day-to-day and month-to-month. Despite all of the email sent, all the documents written, all the images digitized and stored, all the websites accessed, the average desktop computer looks exactly the same (minus a bit of surface dust and sticky-notes) as it did the day it was unpacked. By that standard, the desktop computer is about as Protean as the average stone.

It might be replied that this analysis misses the point of Papert’s metaphorical use of the term. Obviously, a “classic” computer is Protean in abstract, symbolic, purposeful ways that are not reflected in surface appearance. But the mundane interpretation of the term is still relevant to the issue at hand—namely, children’s experience of the computer. When computation is imprisoned in a desktop box, equipped with standard keyboard, screen, and (these days) Internet connection, there are only so many types of experiences that one can have of it. The youngster described in Papert’s introduction, after all, fell in love with *objects*—things that

could be handled, touched, smelled, placed on the shelf or in one's pocket, collected, traded, and decorated. Individual gears themselves may not change shape, but a child in love with gears can build toys with them, line them up on the bookshelf, maybe hang them from the ceiling. The look of the child's room—the *setting*—changes shape in ways that reflect a state of intellectual infatuation. For classical computers, that sort of room-sized effect runs against the grain. The “modern-day Montessori” imagined by Papert may indeed have been misguided if she thought that every child should have a gear set; but if she focused on the tangible, artifactual side of the story, thinking about children's relationships with the world of physical stuff, she might have had a good idea in the works.

The “classic” computer is still a wonderful and useful object, and it can still make all sorts of positive differences in children's lives, many of them through precisely the sorts of experiences that *Mindstorms* described and helped to inspire. But computation—and technology, more broadly—affords a much wider range of experience and possibility than suggested by the box on one's desk. In particular, the blending and interweaving of computation and materials science—a process still in its conceptual and implementational infancy—appears poised to extend the intellectual and emotional potential of children's artifacts in the next generation. The sense of energy and optimism that pervades *Mindstorms*—that tone of joy that drew so many of my generation into the book—may thus be justified, perhaps even more powerfully, by the world of objects yet to come.

1.1 Blending Computation and Physical Artifacts for Children; an Outline of This Paper

There are a myriad of ways in which computational and material artifacts may be expressively combined; offering a rigid taxonomy of those ways at this juncture might be counterproductive. For the purposes of this paper, though, the strategies of integration can be very broadly categorized as follows:

Strategy 1. The development of software applications to augment or enrich children's use of tangible materials. The materials in question are often “traditional” craft media (paper, string), but might well include newer and more exotic materials. A closely related theme involves the exploration and use of a wide variety of novel output devices enabling desktop computers to “print out” all sorts of materials.

Strategy 2. Embedding computational capabilities within physical objects. Such “computationally-enriched” objects can be endowed with a wide range of dynamic and communicative behaviors. They may also be combined into larger systems, “kits”, or sets of mutually communicating or interoperable objects.

Strategy 3. The exploration and use of a wide variety of new materials of various levels of “intelligence”, adaptability, expressiveness, educational interest, or potential for integration with computational techniques.

In other words, children can engage in new sorts of craft projects with the aid of computers (strategy 1); they can work with an endless variety of new sorts of computationally-enriched physical objects (strategy 2); and they can explore and appropriate a new landscape of technology in which the notions of “procedure”, “computation”, and “material” intermingle in powerful ways (strategy 3). These strategic categories are not mutually exclusive; indeed, they may themselves be productively blended to produce new “composite strategies” for expanding the range of children’s artifacts. Nor are the categories collectively exhaustive: there are still other broad strategies for integration that might well yield other sorts of artifactual treasures. Still, for the discussion that follows, these three strategies will provide some structure and coherence to the variety of examples that we will employ.

The remainder of this paper will be organized around four central themes within *Mindstorms*:

- the notion of a “transitional object” between concrete and formal reasoning;
- “Mathland” as a cultural setting in which ideas of mathematics become natural, personalized, and humanized;
- the notion of a “microworld”; and
- cultural roles of new technologies.

In the next four sections, we will explore these ideas in turn. In each case, we will first summarize Papert’s presentation of the idea under consideration, and then reinterpret or extend the original idea in the light of an increasingly complex ecology of physical and virtual artifacts. The final section of the paper will summarize the argument and offer some possible directions for further reflection and research in the spirit of Papert’s book.

2. Physical Artifacts as “Transitional Objects”

The gear can be used to illustrate many powerful “advanced” mathematical ideas, such as groups or relative motion. But it does more than this. As well as connecting with the formal knowledge of mathematics, it also connects with “body knowledge,” the sensorimotor schemata of a child.... It is this double relationship—both abstract and sensory—that gives the gear the power to carry powerful mathematics into the mind. In a terminology I shall develop in later chapters, the gear acts here as a *transitional object*. [*Mindstorms*, p. viii; emphasis in the original]

Papert’s first use of the term “transitional object” in the opening paragraphs of *Mindstorms* makes explicit mention of the sensory (as well as abstract) character of such an object. Briefly, the portrait of a transitional object as it emerges in the book is one that enables a bridge between “concrete” and “formal” stages of reasoning (where the terminology is taken from, but not excessively beholden to, the developmental theories of Piaget). There is more than a little resonance between the notion of transitional object as presented in *Mindstorms* and the literature surrounding the use of mathematical manipulatives (such as number rods and balancing scales): both are conceived as objects that achieve a natural fit with children’s early understanding of the physical world, and both act as sources of examples and images for a transition to a more formal realm of abstract symbolic reasoning.² But Papert’s notion is much more attuned to the affective role that a transitional object can play—and in this sense, the transitional object has a more interesting connotation than “merely” a manipulative. It becomes something at least a little closer, in the emotional realm, to a favorite toy or stuffed animal.³

The quintessential transitional object, as discussed in *Mindstorms*, is the Logo turtle—a “mathematical creature” that can move forwards or backwards and turn right or left in response to programmed commands. In its earliest instantiation, the turtle was a physical robot (a “floor turtle”); but by the time of the publication of *Mindstorms*, most references to the turtle had come to focus upon its later and more widely recognizable form as a kind of “programmable pen” for the computer screen. This later version (the “screen turtle”) is a purely virtual entity, drawing graphical lines and (given the appropriate commands) complex geometric patterns.⁴ The turtle is an object with which children can identify through body movements; yet it is at the same time an object that brings to life a wealth of mathematical ideas in (among many other areas) group theory, differential geometry, and cybernetics.⁵

Importantly, the link to formal reasoning through the turtle is effected in large part by a procedural language (Logo); it might not be unfair to say that the turtle-plus-language system as a whole acts as the true transitional object in the book.

2.1 *The Emotional Life of the Transitional Object*

[T]he “laws of learning” must be about how intellectual structures grow out of one another and about how, in the process, they acquire both logical and emotional form. [*Mindstorms*, p. vii]

There is a productive tension in the language that surrounds transitional objects (and their mathematical-manipulative cousins). On the one hand, there is an intended universality—or at least broad applicability—of transitional objects in their role as a cognitive bridge. Presumably, many children have common experiences with physical objects that make number rods and turtles such powerful carriers of mathematical ideas. On the other hand, a rich theory of transitional objects would probably highlight their variety and personal resonance for individual children—the more affective or aesthetic side of the objects’ roles. Not all children respond with intensity to the particular affordances of the turtle (just as not all children respond to gears, or any other particular example of a transitional object).

It is along this dimension—of the personal, the emotional, the socially connected, the aesthetic—that the (screen) turtle is most potentially limited, in large part because of its disconnection from the material life of the child. Consider the things that a screen-based transitional object, of any sort, cannot be: it cannot be large and inhabitable; or collectible; or huggable; or something that you give to your parents; or something that you miss when you take a trip and leave it at home; or furry; or a million other things.

These are not quibbles. It is not unreasonable, as the quote that begins this subsection suggests, to expect that transitional objects might be experienced by children as *simultaneously* cognitive and emotional artifacts. Indeed, it seems arguable that there is a connection between (on the one hand) the universal side of transitional objects and their cognitive roles; and the personal side of these objects and their affective roles. In other words, there might be a relatively universal analysis of how children develop basic mathematical notions such as numbers, functions, or inverses; but the analysis must become highly individualized and

narrative-driven when those mathematical notions are realized in the form of emotion-laden experiences and objects in children's lives.

And it is precisely at this meeting place between cognitive universals and affective particulars that the design of transitional objects must take place. For some children, the emotional affordances of screen-based entities will be just right (or at least sufficient) to serve as transitional objects; for others, the limitations of the form will prove insurmountable. There has been a general lament, since the publication of *Mindstorms*, that relatively few tasteful successors to the turtle have been devised. But, given the aesthetic and physical constraints of the classic computer, it is hardly surprising that coming up with good transitional objects has been difficult; if anything, it's remarkable that something as powerful as the original screen turtle managed to emerge at all.

2.2 Transitional Objects and Formal Languages

How, then, might we rethink the design of effective transitional objects in the light of new material technologies? The example of the turtle suggests that we might look to children's activities in which the use of materials is both rich in potential mathematical content, and naturally linked to formal (or quasi-formal) notations—"languages", or their natural precursors—for design. The sorts of activities implied here include: origami, weaving, knitting, model building, bead stringing, mosaic tiling, and many others.

To take one concrete example, consider the activity of weaving geometric shapes out of long strips of paper tape. This activity is briefly mentioned in Cundy and Rollett's invaluable book *Mathematical Models*⁶, and begins by making simple folding patterns on the strips; these patterns may then be used to make the elementary folds from which still more complicated patterns may be woven. Figure 1 (from Cundy and Rollett) shows several sketches that introduce the basic paper-tape patterns. Figure 2 continues the development by showing how one remarkable craftsman, Heinz Strobl⁷, has used paper tape to create impressive mathematical sculptures.

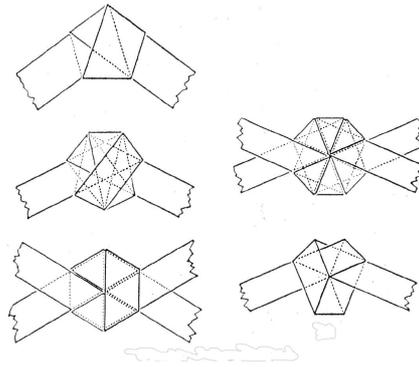


Figure 1. Several “primitive” paper tape knot designs. (From Cundy and Rollett [1961].)

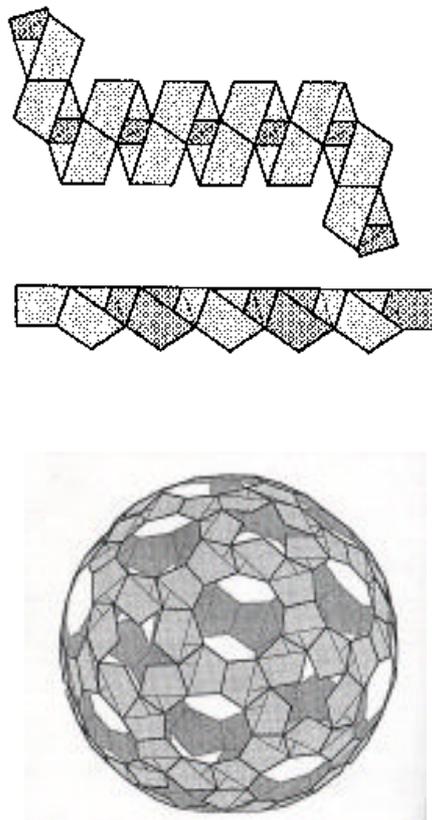


Figure 2. Representative means of linking together paper tape knots into larger sequences (top), and a three-dimensional hollow figure created from paper tape knots (bottom). (From Strobl [1997].)

The immediate point of this example is to indicate the possibilities for developing a formal notation for paper-tape design. Indeed, the growth of pattern and complexity sketched in Figures 1 and 2 irresistibly suggests the paradigm of formal language

development that is at the heart of Abelson and Sussman's⁸ influential portrait of computer programming. That is, in this particular example, small "primitive" elements of a paper tape language are combined (via several characteristic means) into larger patterns, which are again combined into still larger patterns. A natural next step, then, would be the development of a software application (perhaps along the lines of the HyperGami system created in our lab⁹) in which students could experiment with combinations of paper tape patterns on the screen and create recipes for the physical design of magnificent three-dimensional paper tape sculptures.

There is a larger point at issue, here, however, beyond our particular example. Paper tape—or a "paper tape/language system"—is, of course, only one instance of a potential transitional object. It is hardly to be expected that this is any better, as a single instance, than gears or screen turtles. But there are many such activities, and each one has its own particular mix of intellectual and emotional affordances for children. Paper tape, as a medium for creation, is fragile; but mosaic tiles are not. Paper tape designs cannot realistically be worn as clothing; but woven knot patterns in fabric, or bead constructions, can. On the other hand, one could imagine using hollow paper tape constructions (such as the one shown in Figure 2) as frameworks to house still other objects, such as chimes; or as (very elaborate!) forms of gift-wrapping; or, in large, oversized versions, as the frameworks for indoor geodesic-dome-like structures.

More broadly, what is being suggested here is the use of strategy 1 (in the list from the previous section) as the initial basis for exploring a huge, and largely uncharted, space of possibilities for creating procedural and mathematically rich notations for material design. This is a reasonable description of at least several of the projects undertaken in our lab at the University of Colorado, and it also recalls the work of Carol Strohecker in designing procedural notations for knot-tying¹⁰; but in any event, those projects have focused on only a few examples out of literally dozens that might be tried.

Children's craft activities, then, are a likely source of transitional objects in the sense of *Mindstorms*; and a reasonable way to proceed, for educational technologists, would be to create software applications that endow these activities with symbolic notations. Going just a bit further, we can hope that the design of new output devices (such as—to pursue the earlier example—a paper tape printer) could still

further enrich the “transitional object” role of craft materials, allowing children not only to design (in software) but also to “print out” a far wider range of creations.¹¹

3. “Mathland” as Physical Setting

Two fundamental ideas run through this book. The first is that it is possible to design computers so that learning to communicate with them can be a natural process, more like learning French by living in France than like trying to learn it through the unnatural process of American foreign-language instruction in classrooms. Second, learning to communicate with a computer may change the way other learning takes place. The computer can be a mathematics-speaking and alphabetic-speaking entity.... The idea of “talking mathematics” to a computer can be generalized to a view of learning mathematics in “Mathland”; that is to say, in a context which is to learning mathematics what living in France is to learning French. [*Mindstorms*, p. 6]

The notion of “Mathland” is one of the most compelling and beautiful in *Mindstorms*: it calls to mind an image of an entire culture, a lived-in world, in which mathematics is playfully embedded within all sorts of activities. The quote above, in particular, homes in on the notion of immersion—twice within one page, Papert compares the experience of being in Mathland to that of “living in France”.

Immersion—that feeling of being within a supportive surrounding environment—is something that classic computers are rather limited at providing. Certainly, a student sitting at a computer can become deeply engrossed in a programming task or a video game; but eventually, she must get up from the chair and return to a world in which mathematics is generally suppressed, left undiscovered, or associated with aesthetically sterile objects and artifacts such as times tables.

Imagine how a child’s room in our ideal Mathland might actually look—what objects might actually appear. There might be:

- A mobile of homemade polyhedra hanging from the ceiling;
- A dynamic cellular automaton design on one wall, playing a game of Life (this wall-sized dynamic artwork could be reprogrammable, so that other cellular automaton rules could be tried);

- A miniature, personalized “Stonehenge” observatory made of imitation stone. The child’s Stonehenge would be placed beside the window, and designed so that on certain days of the year (e.g., the solstice, or days preceding a lunar eclipse), the sun would catch the pieces of the observatory to produce shadows or light patterns in particularly striking or informative ways on the bedroom wall;
- Wallpaper that periodically changes its design to cycle (say, over the period of a month) through all seventeen planar symmetry groups; design elements shown on the wallpaper could be controlled or input by the child from a desktop computer;
- A glow-in-the-dark mathematical string sculpture, or weaving, whose appearance changes as the fibers of which it is composed alter their color in response to a simple (user-written) program;
- Homemade or custom-designed topological ring-separation puzzles, wooden burr puzzles, or balancing animal figures (the sort that dangle, apparently miraculously, over the edge of a shelf).

Some of these imagined artifacts could be created straightforwardly with existing technology; others are mildly (but only mildly) futuristic, predicated on the increased availability, affordability, or usability of novel materials such as “programmable paper” and electronically controlled glowing wire.¹² Most likely, no child’s room would include *all* of these artifacts (the overall effect might be aesthetically jarring!), but even a couple of them might make for a gorgeous environment; and the list shown here could be extended for pages in joyful brainstorming sessions.

The crucial point, in any event, is not the feasibility of any particular example. Rather the point is that, in thinking of what “Mathland” might mean, *the room, and not the computer screen, is the most tasteful and productive grain size of design for educational technology.* That is: as educational technologists, we should try to imagine what the child’s room (or maybe the classroom) might look like, not merely what sort of interface is provided on a computer screen.

Designing at the level of the room permits us, as technologists, the creative leeway to imagine new sorts of rugs, wall hangings, mobiles, windows, wind chimes, ceiling tiles, and so forth. In many cases, these artifacts could be child-designed, or child-and-parent-designed, or child-controlled (at least partially) via computer. The affordances of such objects allow for a sense of the immersion to which Papert alludes: Mathland, for the child, could be the sort of place in which one wakes up, plays with friends, thinks about life, and goes to sleep.

Naturally, one could take this analysis a step further, and imagine a still larger scope for Mathland—the entire school building, say, or the home, or the neighborhood. Thinking at this scale might be inspiring, but my own belief is that room-sized design, at the current state of technology and infrastructure, constitutes the most productive path for educational technology. The neighborhood is too large a canvas to make much progress; the computer screen is too small a canvas to have much effect on a child’s life. The room is the scale at which the long-imagined Mathland might come into existence; and to work at that scale, we need to pursue technologies for child-centered construction and design in all sorts of physical materials.

4. Towards the Physicalized Microworld

It is in fact easy for children to understand how the Turtle defines a self-contained world in which certain questions are relevant and others are not... [T]his idea can be developed by constructing many such “microworlds”, each with its own set of assumptions and constraints. Children get to know what it is like to explore the properties of a chosen microworld undisturbed by extraneous questions. In doing so they learn to transfer habits of exploration from their personal lives to the formal domain of scientific theory construction. [*Mindstorms*, p. 117]

The notion of a “microworld”, as it emerges in the pages of *Mindstorms*, acts as a sort of emotional inverse to the notion of Mathland. Whereas the image of Mathland suggests (as noted earlier) pleasurable immersion—a cornucopia of cultural artifacts in which to adventure and explore—the image of a microworld by contrast suggests self-containment, purity, simplicity, and seclusion. (Papert later refers to microworlds as “incubators”, which again reinforces the simile between microworld and cocoon.)

Mathematically, the notion of a microworld calls to mind highly constrained structures for study, such as small finite groups, or the operations of arithmetic modulo a small integer, or the moves of a highly approachable game such as Nim or checkers. Indeed, Papert’s first concrete example of a microworld, shortly following the quote above, is told through the story of a sixth grade girl named Deborah who, initially overwhelmed by the sheer range of possible Logo turtle expressions, deliberately limited her choice of turtle angle-turns to sequences of “Right 30” commands. In mathematical terms, Deborah was working with a group of

operations equivalent to the group of integers under addition modulo 12; in emotional terms (the real point of the story), “for Deborah it was exciting to be able to construct her own microworld and to discover how much she could do within its rigid constraints.” [p. 118]

A microworld, then, can be interpreted as a safe intellectual haven—a cognitive space in which ideas can be explored independent of the complications of such things as arbitrary rational numbers, friction, and playground politics. The classic computer is a rather good medium for such cognitive spaces—not only because small constrained sets of linguistic expressions (such as sequences of “Right 30” turns) define the boundaries of symbolic or notational worlds, but also because the computer screen itself is a small self-contained world in which to work.

Nonetheless, viewed as an emotional haven, there are interesting limitations to purely virtual microworlds—limitations that might be overcome, at least for some children, by physicalized realizations of the kinds of safe-and-simple intellectual structures suggested in the pages of *Mindstorms*. After all, what constitutes comfort, or a feeling of safety, is highly personal—it is likely to be as idiosyncratic a judgment as any person, child or adult, is called upon to make. We might therefore look once more to the material world for alternative media in which to realize the positive cognitive and emotional effects of microworlds. The remainder of this section develops this idea through one particular genre of physical artifact.

4.1 Computationally-Enhanced Construction Kits as Material Microworlds

The most natural physical analog to the sort of microworld described in *Mindstorms* can be found in the realm of construction kits. One might regard (for instance) the beautiful Zometool system¹³ of struts and connectors as constituting a constrained (but still highly productive) cognitive world in which to explore geometry: an “incubator” for geometrical construction. (To provide the reader with a visual sense of this particular commercial kit, Figure 3 shows a photograph of a Zometool polyhedron.) Because Zometool connectors can only link struts at prescribed angles, and because the struts themselves are only at certain prescribed lengths, a student using the system can produce some polyhedral forms (e.g., an icosahedron) but not others (e.g., an arbitrary rectangular prism). In this sense, the constraints of Zometool act much like the protective boundaries of Deborah’s “Right 30”

convention; and a student could even take the idea further by voluntarily restricting her Zometool constructions to certain types of struts.

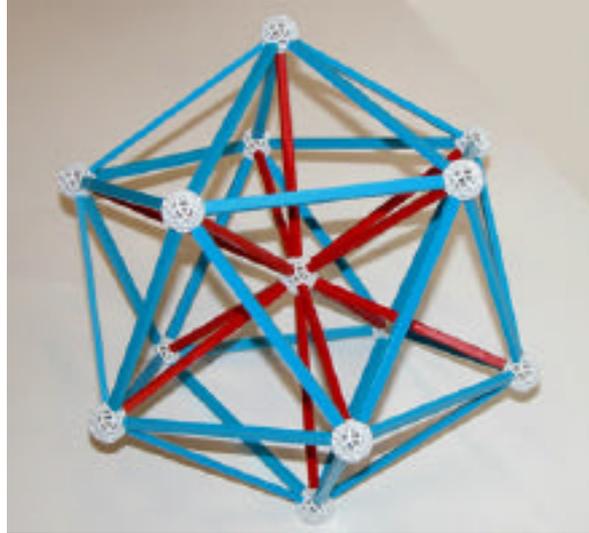


Figure 3. A Zometool model of an icosahedron, composed of struts (the red and blue pieces in the construction) and connectors (the white pieces visible at vertices).

Similar observations could be made of a wide variety of (noncomputational) physical construction kits, ranging from children’s building blocks (at the preschool level) to architectural building kits and molecular modeling sets (at the professional level). Typically the limitations of these sets (in types or numbers of pieces), or the restrictions on the ways in which pieces may be combined, constitute the useful boundaries of a microworld in which to explore—a physically-realized formalism, much like the twelve notes of the musical scale or five basic positions of ballet.

Beyond these intellectual considerations—construction kits as productively constrained, self-contained cognitive worlds—the kits also have emotional affordances missing from screen-based microworlds. For example, kits—especially those conceived for younger children—are often designed so as to permit *big* constructions, at the size of the child or greater. It is not hard to find commercial images in which children are shown creating constructions that surround, dwarf, or contain them: Figure 4 shows several representative examples. Such images of children and their constructions in fact suggest the sense of comfort or safety evoked by the language and examples in *Mindstorms*: the construction is portrayed as a friend, pleasurable setting, or joyful container.



Figure 4. Portraits of children with comforting/surrounding construction kits, taken from commercial sites on the World Wide Web.¹⁴ Upper left: Lego soft bricks. Upper right: the Hoberman sphere. Bottom: Unit blocks.

Still other aspects of (at least some) construction kits are also relevant to the theme of emotional comfort and safety. Children’s model railroad sets—again, particularly those designed for the younger audience, such as Brio sets¹⁵—are more notable for the way in which they develop an entire setting, rather than an individual pattern of railroad track. In other words, much of the appeal of these sets lies in the way in which they evoke a peaceful or comfortable world, replete with trees, shops, farms, railroad shelters, and so forth. The same can in fact be said of more adult-hobbyist-oriented model railroads (and related model settings, such as those used to portray wintry villages for Christmas decorations). For such construction kits, the emotional pull lies in the creation of a place—perhaps a place that is a little low on excitement, but that compensates with a sense of permanence and security. These are “microworlds” in the most direct possible interpretation.

Thus far, the discussion of physicalized microworlds has focused on “noncomputational” construction kits of traditional design. As noted, these kits share some of the intellectual and emotional features of the sorts of microworlds discussed in *Mindstorms*; but there are also numerous ways in which these beneficial features could be enhanced by enriching traditional construction kits with computational elements, utilizing all three of the strategies outlined earlier. That is to say, software applications can help children in designing new or elaborate constructions (strategy 1); construction kits can be augmented with pieces designed and printed by children themselves (strategy 1, in its focus on output devices); pieces with embedded computers could communicate with each other, with desktop machines, or with their users (strategy 2); and experimental pieces can be created from a variety of novel or exotic materials (strategy 3). A sampler of possible scenarios follows.¹⁶

- *Applications for design and construction.* One way of augmenting the experience of using construction kits would be to design software applications that develop languages or notations for construction, as discussed for craft activities in section 2 earlier. (That is to say, one could view construction kits as a particular genre of “transitional object” in the sense already discussed.) The LDraw/LEdit freeware program¹⁷ for creating and editing Lego models on the computer screen could be viewed as a pioneering attempt along these lines (although the notation appears rather unwieldy, and does not, as far as I know, include anything along the lines of an end-user language). More ambitiously, we could imagine systems in which children could (say) write programs to produce graphical versions of Zometool constructions on the screen, and then print out directions for building those constructions out of physical pieces. The advantage of such computer applications is that they provide a means by which children can begin to link symbolic notations—or perhaps a whole variety of notations—with the constructions that they build, and thus can use construction kits as a cognitive playground for employing multiple representations in design.

- *Customized (printed-out) construction kit pieces.* Rather than view construction kits as fixed sets of pieces, unalterable by the user, we can begin to regard such kits as “starter sets” to be augmented by children themselves with the aid of such output devices as 3D printers and laser cutters. One might, for example, imagine a computer system through which children could in fact create and print out their own pieces to augment or personalize commercial construction kits. While such a scenario might suggest a loss of simplicity or “purity” in the construction kit—after

all, now a child might expand a set of pieces in potentially complex or unpredictable ways—at the same time, this sort of activity would permit children to personalize their constructions in idiosyncratic and potentially emotionally compelling ways. A model railroad city might look a bit more like a child's own particular fantasy, for instance; or a Fuller-esque geodesic dome might be constructed in a size to fit a child's favorite doll, using custom-printed Zome (or Zome-like) struts; or a laser cutter might be used to engrave the pieces of architectural constructions with personalized text or designs.

- *Communicating systems of pieces.* By embedding computational elements within construction kit pieces, it should become possible to design kits in which pieces can communicate information to each other and to desktop machines. A crucial advantage of such a scheme is that pieces can “know” the construction of which they are a part. Traditional kits lack this capability: a student might, for instance, construct a model of a molecule of (say) formaldehyde in a chemical modeling kit, and not know that she has constructed a meaningful or interesting molecule. In a computationally-enhanced molecular construction kit (where each atomic piece contains a small embedded computer), the student could bring her sample molecule over to a desktop computer and connect this newly-constructed molecule to the computer (e.g., via wire or infrared communication); the computer could then inform the student of the molecule that she has created. This scenario is merely a hint of what could be imagined by endowing construction kit pieces with computation and communication; an impressive number of explorations along these lines, by various researchers and at various stages of implementation, are currently in progress.¹⁸

- *The possibilities of new materials.* The existence of new, “intelligent” materials—materials that lend themselves particularly well to integration with computational control—suggests a variety of directions for exploring new types of construction kit design. For instance, shape memory alloys are metallic alloys that change shape (e.g., from a “straight” to a “curved” wire shape) in response to a temperature change (which can itself be generated by an electric current). Thus, by embedding shape memory alloys within construction kit pieces, one can design pieces that change their shape or appearance under computational control. Piezoelectric materials can (in a similar vein) change their length along a particular axis under computational control; some recent plastics may be caused to generate light (i.e., these materials emit light when a voltage is applied across them¹⁹); while some glass materials can have their level of light absorption controlled by a

program.²⁰ These and a multitude of other developments in materials science suggest the possibility of creating construction kits whose behavior can be controlled in extremely subtle ways (more subtle than, for instance, the traditional means of including electric motors in constructions). Constructions can (conceivably) bend, expand, pulsate, glow, or change color in response to programs embedded within their individual components.

All of the (very sketchy) scenarios mentioned here could be described at much greater length, but this would cause too lengthy a detour for our particular purposes. The main purpose of providing this list is to suggest the ways in which the notion of a “microworld” may be profitably rethought as a partly computational, partly tangible entity. The argument here has focused on construction kits as the foundational “objects-to-think-with”, as these provide plausible examples of children’s artifacts that can be, at the same time, simple, self-contained in the choice of primitive pieces and means of combination, rich in content, connected with languages and symbolic notations, and suggestive of comfort.

5. The Cultural Appropriation of New (and Old) Technologies: How Should We Think about Stuff?

All builders need materials to build with.... In some cases the culture supplies them in abundance.... But in many cases where Piaget would explain the slower development of a particular concept by its greater complexity or formality, I see the critical factor as the relative poverty of the culture in those materials that would make the concept simple and concrete. [*Mindstorms*, p. 7]

The research challenge is clear. We need to advance the art of meshing computers with cultures so that they can serve to unite, hopefully without homogenizing, the fragmented subcultures that coexist counterproductively in contemporary society. For example, the gulf must be bridged between the technical-scientific and humanistic cultures. And I think that the key to constructing this bridge will be learning how to recast powerful ideas in computational form, ideas that are as important to the poet as to the engineer. [*Mindstorms*, p. 183]

Perhaps the most compelling of all the very compelling ideas in *Mindstorms* is not associated with any one catchphrase like “Mathland” or “microworld”. It is, instead, a steady note of hope and optimism that can be heard throughout the book—a democratizing impulse focused on the relationship between people and technology. It is hard to boil down this idea into a sentence or two, but the quotes above are representative. Papert envisions a world in which technological artifacts are designed to make profound concepts understandable and expressive; and he sees the spread of affordable computers as a means toward knitting together disparate intellectual subcultures. It is difficult now to recapture just how striking this idea would sound in 1980—a time when personal computers were just beginning to appear, and the still-reigning portrait of the computer was as a high-powered business or laboratory device, suitable only for (and understandable only by) a vaguely defined elite. The idea that children might actually *program* and thereby master these instruments (rather than, say, simply play their designated roles as the pupils of “teaching machines”) must have sounded shocking or exhilarating, depending on one’s point of view. At the same time, Papert’s book was also reflective of a certain growing spirit-of-the-age: with the advent of a hobbyist computer culture in the late 1970’s came a new generation of students empowered by the sense of mastery of the devices. Computers could be opened (literally), reconfigured, programmed and (to a considerable extent) understood down to the level of assembly language. (A history of the early years of computing that captures this spirit can be found in Levy’s book *Hackers*²¹; and Bennahum’s memoir *Extra Life*²² provides an often moving personal account of how it felt to be a student mastering the hobbyist-level computer.)

One could make the case that recent history, in this regard, has proven something of a disappointment. Although desktop computers are undeniably more affordable and ubiquitous than they were a generation ago, I would argue that they are at the same time less appropriable by children or adults. This is, in some ways, a delicate argument to make: the modern computer is certainly more usable than before, in the sense that it is much easier to employ powerful applications than at any time in the past. But a machine that is easy to use is not the same as a machine designed to be understood, learned, or mastered. The modern desktop computer—like many other sophisticated devices in Western culture—is designed, effectively, to work like magic and to shut its users out of the culture of design and participation. By this measure, the relatively simple, “open-able” hobbyist machines of the late 1970’s and early 1980’s were in fact more in the spirit of *Mindstorms* than the current sleek models. The computer has effectively taken its place beside the television as a

magical instrument not to be tinkered with—more interactive than the television, to be sure, but nonetheless a medium of pre-supplied, expensively-produced, highly complex, and (for the most part) nonprogrammable and incomprehensible systems. Moreover, while children’s programming is still practiced (e.g., through systems such as Logo or Cocoa²³), it apparently represents a relatively small fraction of children’s computational activities.²⁴

It might be argued that the World Wide Web is a counterexample to the argument above—that for children, perusing and (occasionally) contributing to the Web is the modern-day equivalent of the type of activity promoted by *Mindstorms*. This may have some mild degree of truth; but even if many more children were actually creating (rather than simply viewing) websites, the sort of activity involved in creating the average website is far less revolutionary in spirit than the sorts of activities discussed in *Mindstorms*. That is to say, the language of Papert’s book continually emphasizes the possibility of radically rethinking domains such as mathematics, physics, and even physical skills (such as juggling)—of coming to these subjects with an entirely new repertoire of cognitive skills derived from procedural metaphors. Most website creation, whether it’s done by children or adults, is far more mundane than this.

5.1 *Materials and Computation: a Return to the Hobbyist Subculture*

There is some reason to believe that the hope of a new era of appropriable, democratized technology could be revived through precisely the sorts of combined physical/virtual artifacts envisioned in this paper. That is to say, the various strategies for integrating computers and materials outlined in the first section could, if actively pursued, collectively lay the foundation for a return to the “hobbyist” subculture of personal computing that formed the historical backdrop for the enthusiasm visible in *Mindstorms*. While space does not permit a thorough unpacking of this argument here, the following paragraphs are meant to provide a variety of hints, or initial forays, toward a more elaborate version of this thesis.

- *Programming in the small.* One of the recurring difficulties with end-user programming (and by extension, children’s programming) is that it is often necessary to create rather large or complex programs in order to achieve some desired effect: a child who wishes to create a full-fledged original video game, for example, must be both motivated and prepared to write a sizeable amount of

organized program text. This rapid growth of project complexity tends to mediate against the spread of informal programming, and to make of programming a purely professional art.²⁵ In contrast, programming-in-the-small has a particular hardness when employed in the context of embedded computation (i.e., “strategy 2” in the earlier list). As users of the programmable Lego brick well know, very small programs can produce dramatic effects when those programs are used to dictate the behaviors of physical objects. Arguably, then, the proliferation of programmable objects—physical artifacts that can be endowed with a (usually minimal) degree of controllability—could spawn a widespread revival of democratized, informal programming.

- *Technologically-Enriched Collectibles.* One of the most powerful recurring themes within existing hobbyist subcultures is that of collecting—of achieving a “complete set”. This mysterious urge is visible in children’s culture no less than adult hobbyist circles. Children over time have collected trading cards, marbles, butterflies, construction kit pieces, and myriad other naturally-accreted objects. We can certainly speculate on the origins of this sort of activity, but it is undeniably an overwhelming urge in many children’s cognitive and emotional lives. Consider, then, the ways in which a blending of computation and materials science could produce new, and intellectually powerful, collectibles. Such objects could be (e.g.) a complete set of custom-decorated classical polyhedra; or a collection of customized working mechanical elements²⁶, each one designed on a computer and then “printed” in wood or metal; or a set of “programmable trading cards”, each made from a small quantity of “programmable paper” and running (e.g.) a personalized graphical effect. By exploring examples such as these, a variety of hobbyist “collector cultures” could arise, each one independently supporting research and development in democratized technologies.

- *Building upon Existing Hobbyist Subcultures.* The discussion of the previous paragraph focused on the broad notion of “collecting” within hobbyist cultures. More generally, the integration of computation with materials can potentially find a home in any number of existing hobbyist cultures. That is, one could imagine (and in some cases, one can already witness the dawn of) a technologically-enriched version of the design of puppets or dolls; the creation of party favors; the design of homemade ornamentation and jewelry; the creation of miniature towns; home woodworking; and weaving. Each of these established hobbyist communities could well find compelling reasons to adopt new computational tools, languages, and materials to enhance their existing practices. This in turn

could form the social bedrock for a widespread re-emergence of personalized programming and amateur scientific research.

The overall point of the previous paragraphs is to provide some renewed optimism about the possibility of personally controllable technology. Just as a wave of “citizen hackers” in the 1970’s first appropriated the tools of home computation (and, just as, arguably, an earlier generation of citizens appropriated radio technology in the first decades of the twentieth century), a new wave of “hobbyist hackers” could blend computation and tangible materials during the decades to come. Should this happen, the joyful, empowered spirit of *Mindstorms*—a spirit closely linked to the emotions that accompanied the early spread of home computation—could achieve a renewed vigor in the coming century.

6. Conclusion: from Mindstorms to Mindstuff

The argument of the previous sections may now be restated, in distilled form. Briefly: a child who falls in love with gears has probably—and for good reasons—fallen in love for life. And for those of us who recall that reading experience from two decades ago, there is still ample reason to be in love with *Mindstorms*. The goals of the book—to focus attention on how technology can change our deepest thoughts and images, to imagine such wonders as “microworlds” and “Mathland”, to point toward a notion of technology so humanized that children can make it their own—these are still far-reaching, compelling goals. The central technological example of the book—namely, the “classic” computer and the associated particular language system (Logo) accompanying it—were rather narrowly conceived artifacts. As such, they were good objects-to-think-with, and continue to be so; but they are relatively constraining objects-to-adhere-to.

What do the computers of *Mindstorms* lack? Why is it that physical objects, in all their variety, are so crucial to the creation of rich educational environments? Or, to put the matter another way: what do physical objects provide for children (and adults) that the plethora of software “worlds” inside the desktop computer do not? Probably the most thoughtful psychological research on the “human-physical object relationship” can be found in Mihalyi Csikszentmihalyi and Eugene Rochberg-Halton’s [1981] full-length study *The Meaning of Things*²⁷. This book is based upon interviews with 82 Chicago-area families; the questions focused on the important

objects in the lives of the interviewees. It is impossible to summarize here the remarkable breadth of the authors' observations on these interviews, but for our purposes one paragraph is sufficiently provocative to warrant quoting in full:

The outline that emerges from these findings is not surprising on the whole, but it allows us to see with greater clarity and detail how the self develops and is maintained across the life span. The importance of objects of action in the early years is a reminder of the powerful need children have to internalize actions and to define the limits of their selves through direct kinetic control. The internalization of the other and the experiences of our own inadequacy are extremely important for the cultivation of the self and are often painful. But intentional action producing enjoyment is also central to the evolution of the self. Enjoyment is a key factor because it serves as proof that the action is a genuine expression of the self. Therefore play, toys, and tools used in games have a central importance in the development of children. [Csikszentmihalyi and Rochberg-Halton 1981, p. 100]

The quote above highlights a theme that runs through Csikszentmihalyi and Rochberg-Halton's book: namely, the role of objects in the evolving definition of "self" within people's lives. Physical objects—"objects of action", and the various ways they afford of experiencing "direct kinetic control"—are woven individually and idiosyncratically into children's intellectual and emotional lives.

Csikszentmihalyi and Rochberg-Halton's observations resonate with those that my colleagues and I have made on previous occasions regarding the products of children's handcrafting activities. In the course of our HyperGami work, we have noted that objects such as customized paper polyhedra have affordances for children that seem to transcend their purely mathematical content. Such craft objects also have what we have called "social currency" in students' lives: polyhedra can (for example) be given as gifts, put on display at home or in the classroom, kept as souvenirs, and endowed with names. It is hard to explain precisely why purely computational artifacts (programs, simulations, graphics files, and so forth) resist this type of usage—one *could* give a simulation, or personally-written program, or graphics file, as a gift, and one *could* keep such a thing as a souvenir—but these abstract entities seem somehow ill-fitted for this sort of role.

This is not to say that "classic" computational artifacts may not also be important in children's lives; nor is it to say that all those things that children *do* find important

(as in the original interviews) need be regarded as educationally worthwhile. Csikszentmihalyi and Rochberg-Halton's observations were made before the explosion of the personal computer; and just as large numbers of young interviewees mentioned stereos and television as "important objects" in their original interviews, it is likely that—if the interviews were to be conducted today—desktop computers and game machines would be prominently mentioned. How children relate to the virtual artifacts associated with these objects, in comparison to how they relate to physical objects, is a large subject in need of much further study; and the intellectual or cognitive value (or lack of value) of the most popular commercial artifacts targeted at children (such as video games or television programs) is likewise a vast subject well beyond the scope of this paper. But in any event, the argument of this paper is that many of the most compelling, expressive, and tasteful aspects of "classic" educational computing may be integrated with the most compelling, creative, and valuable educational properties of physical objects.

And this brings us back to Papert's book. The advent of a newly-interwoven material/computational technology opens up numerous paths by which the goals of *Mindstorms* can be effectively pursued. Not all children are captivated by a screen on a desk. But an anthropological view of children—a view of childhood itself, as played out in the lives of boys and girls over the preceding centuries—suggests the things that children find important and compelling. Activities with stuff are what children do, what they have always done.²⁸ Whether they are playing with marbles or yo-yos or trading cards or string figures or tops or blocks or shadow puppets, children (and adults) find a strange fascination and solace in the touchable world. And these various traditions of beautiful objects can, I believe, become productively interwoven with new physical and computational materials. Thus, rather than hoping to revolutionize the cognitive worlds of children with an aesthetically limited form of computation, we can instead, as technological designers, begin by watching the "people in the playground".²⁹ From that observational starting-point, we can collaboratively reimagine the most tasteful objects of childhood in still more expressive forms.

A focus on physicalized computation, integrated with new and traditional craft materials, likewise enables us to rethink the role of educational technology within larger, and perhaps disparate, global cultures. We can look to various children's cultures around the planet; and we can explore how children's activities with materials might lend themselves to robust, creative, emotionally and intellectually inspiring integration with technological artifacts. Children in particular regions of

the world may find that the materials to hand include (say) ceramics, or glass, or wool, or copper, or beautiful varieties of wood. Such materials may suggest particularly compelling educational innovations. Admittedly, the successful integration of a very little bit of well-chosen computation (or novel materials) with local materials and crafts may seem like a utopian goal; but it is perhaps a more realistic goal than the idea that one overarching form of computational artifact (whether the “classic” computer, the Logo turtle, or whatever) would find equally receptive cultural ground all over the globe.

Computers are, in fact, not at all Protean; but computation, behaviorally rich materials, and traditional materials—taken in combination—are. Realizing the deeper goals of Papert’s *Mindstorms* through this expansive notion of technology is—in my view—achievable, desirable, and quite arguably a moral imperative for the community of educational technologists and designers.

Acknowledgments

This paper reflects the influence of a large number of people (though they might disagree with some or all of the ideas expressed here). I am particularly indebted to Hal Abelson, Wally Feurzeig, Mark Gross, Fred Martin, Michael Mills, Mitchel Resnick, Andee Rubin, Carol Strohecker, and Uri Wilensky. Amy Bruckman and two anonymous referees provided extremely helpful comments on an earlier draft of this paper. Colleagues here at CU who have contributed to and/or influenced this work include Ann Eisenberg, Gerhard Fischer, Mitchell Nathan, Chris DiGiano, Julie DiBiase, Glenn Blauvelt, Susan Hendrix, Thomas Wensch, Ted Chen, and Hal Eden. Ideas about construction kits were strongly influenced by the design work of Khomkrit Kaowthumrong, Nathaniel Lee, and Will Lovett. The work described in this paper has been supported in part by National Science Foundation grants REC0125363 and REC0106976, and by a gift from Mitsubishi Electric Research Laboratories (MERL) in Cambridge, Massachusetts.

Notes

¹ Papert, S. [1980] *Mindstorms*. New York: Basic Books.

² A provocative discussion, from the perspective of cognitive science, on the physical origins of mathematical understanding, may be found in: Lakoff, G. and Núñez, R. [2000] *Where Mathematics Comes From*. (New York: Basic Books). For discussions of some of the central current research issues surrounding the use of manipulatives in mathematics education, see for example: Ball, D.L. [1992] Magical hopes: manipulatives and the reform of math education, *American Educator* (Summer), 15-18;46-47; as well as the introductory sections of Hall, N. [1998] Concrete Representations and the Procedural Analogy Theory, *Journal of Mathematical Behavior*, 17:1, pp. 33-51, and Chao, S.; Stigler, J.; and Woodward, J. [2000] The Effects of Physical Materials on Kindergartners’ Learning of Number Concepts, *Cognition and Instruction*, 18:3, pp. 285-316.

³ Probably the most widely-used sense of the term “transitional object” derives from the work of the child psychologist D.W. Winnicott. This more clinical notion of transitional object functions, in fact, primarily in the emotional (and not the cognitive) realm: the typical summary of Winnicott’s thought stresses the infant’s use of an inanimate object (such as a blanket) to substitute for the presence of the mother. Papert’s use of the term is clearly closer to the interests of Piaget than Winnicott, but there are certainly overtones of the “clinical” definition in Papert’s emphasis on the affective role of transitional objects.

⁴ It should be noted that both types of turtles are in fact described in *Mindstorms*, and that the floor turtle is—like the screen turtle—capable of drawing figures (in this case, with a physical pen). Still, the examples shown in the book (see especially Chapters 3 and 5) are heavily weighted toward the graphical features and advantages of the screen turtle; and for the most part, subsequent treatments of turtle mathematics and programming have likewise focused on the screen- (as opposed to floor-) turtle.

⁵ For an inspiring introduction to the subject of turtle-based mathematics, see Abelson, H. and diSessa, A. [1980], *Turtle Geometry* (Cambridge, MA: MIT Press).

⁶ Cundy, H. M. and Rollett, A. P. [1961] *Mathematical Models*. London: Oxford University Press.

⁷ Strobl [1997] *Symmetry in Two- and Three-Dimensional Origami with Knotted Tape*. In Miura, K. (ed.) *Origami Science and Art: Proceedings of the Second International Meeting of Origami Science and Scientific Origami*, Otsu, Japan.

⁸ Abelson, H. and Sussman, G. J. [1996] *Structure and Interpretation of Computer Programs*. Cambridge, MA: MIT Press.

⁹ Eisenberg, M. and Nishioka, A. [1997] Orihedra: Mathematical Sculptures in Paper. *International Journal of Computers for Mathematical Learning*, 1:225-261

¹⁰ See, for instance, Eisenberg and Nishioka [1997]; Eisenberg, M.; Rubin, A.; and Chen, T. [1998] *Computation and Educational Handicrafts: a Strategy for Integrative Design*, in *Proceedings of International Conference on the Learning Sciences, 1998, Atlanta, December*, pp. 84-90; and Strohecker, Carol [1996] *Understanding Topological Relationships through Comparisons of Similar Knots*, *AI & Society* (10) pp. 58-69.

¹¹ An argument along these lines is presented at much greater length in: Eisenberg, M. [2002] *Output Devices, Computation, and the Future of Computational Crafts*, *International Journal of Computers in Mathematical Learning*, 7:1, pp. 1-44.

¹² See, for instance: Mann, C. [2001] *Electronic Paper Turns the Page*, *Technology Review*, March, 2001; and the commercial websites for electroluminescent wire at www.glowire.com and www.thatscoolwire.com.

¹³ Zometool, Inc. (Website: www.zometool.com)

¹⁴ The sources for these commercial images are (upper left, upper right, and bottom, respectively):

www.1on1schoolsupplies.com/legsofbriest.html

www.hoberman.com/fold/sphere/spheres_all.htm

www.1on1schoolsupplies.com/unitblocks.html

¹⁵ Website: www.briotoy.com

¹⁶ More detailed argument along these lines may be found in: Eisenberg, M.; Eisenberg, A.; Gross, M.; Kaowthumrong, K.; Lee, N.; and Lovett, W. [2002] *Computationally-Enhanced Construction Kits for Children: Prototype and Principles*, in *Proceedings of International Conference on the Learning Sciences, Seattle, WA*.

¹⁷ Website: <http://library.thinkquest.org/20551/home.html>

¹⁸ See, for instance: Resnick, M.; Martin, F.; Sargent, R.; and Silverman, B. [1996] *Programmable Bricks: Toys to Think With*, *IBM Systems Journal*, 35:3, pp. 443-452; Resnick, M.; Martin, F.; Berg, R.; Borovoy, R.; Colella, V.; Kramer, K.; and Silverman, B. [1998] *Digital Manipulatives: New Toys to Think With*, in *Proceedings of CHI '98*, pp. 281-287; Gorbet, M.G. et al. [1998] *Triangles: Tangible Interfaces for Manipulation and Exploration of Digital Information Topography*, in *Proceedings of CHI '98*, pp. 49-56; Kitamura, Y. et al. [2001] *Real-time 3D Interaction with ActiveCube*, in *Proceedings of CHI 2001 (Extended Abstracts)*, Seattle, WA, pp. 355-356; Wyeth, P. and Wyeth, G. [2001] *Electronic Blocks: Tangible Programming Elements for Preschoolers*, in *Proceedings of the Eighth IFIP TC13 Conference on Human-Computer Interaction (INTERACT 2001)*; Camarata, K. et al. [2002] *Navigational Blocks*, in *Proceedings of Intelligent User Interfaces '02*, San Francisco, CA.; and Eisenberg et al. [2002].

¹⁹ See: Royal Swedish Academy of Sciences [2000]. *The Nobel Prize in Chemistry, 2000: Conductive Polymers*. Website: www.nobel.se/chemistry/laureates/2000/chemadv.pdf

²⁰ See, for instance, the Sage Electrochromics, Inc. website: www.sage-ec.com

²¹ Levy, S. [1984] *Hackers: Heroes of the Computer Revolution*. New York: Doubleday.

²² Bennahum, D. [1998] *Extra Life: Coming of Age in Cyberspace*. New York: Basic Books.

²³ See: Smith, D. and Cypher, A. [1999] *Making Programming Easier for Children*. In A. Druin (ed.), *The Design of Children's Technology*. San Francisco, CA: Morgan Kaufmann, pp. 201-221. Since the publication of this reference, Cocoa has been renamed "Stagecast Creator".

²⁴ This is a reasonable surmise from the useful data in: Becker, H. J. [2001] *How are Teachers Using Computers in Instruction?* Paper presented at 2001 meetings of American Education Research Association (AERA),

www.crito.uci.edu/tlc/FINDINGS/special3/How_Are_Teachers_Using.pdf, and Wenglinsky, H. [1998], *Does It Compute? The Relationship Between Educational Technology and Student Achievement in Mathematics*, Princeton, NJ: Educational Testing Service, although the topic of programming *per se* is not a specific focus of either paper.

²⁵ Fascinating extended discussion of these issues can be found in a variety of sources: Nardi, B. [1993] *A Small Matter of Programming* (Cambridge, MA: MIT Press); diSessa, A. [2000] *Changing Minds: Computers, Learning, and Literacy* (Cambridge, MA: MIT Press); and the collection edited by Cypher, A. [1993] *Watch What I Do: Programming by Demonstration* (Cambridge, MA: MIT Press). It should be noted that the various authors represented here assuredly would not concur with all of my own views on the subject.

²⁶ E.g., of the sort shown in Clark, W. M. [1943] *A Manual of Mechanical Movements*. Garden City, NY: Garden City Publishing Co.

²⁷ Csikszentmihalyi, M. and Rochberg-Halton, E. [1981] *The Meaning of Things*. Cambridge, UK: Cambridge University Press.

²⁸ Cf. Opie, I. and Opie, P. [1997] *Children's Games with Things*. Oxford, UK: Oxford University Press.

²⁹ From the title of: Opie, I. [1993] *The People in the Playground*. Oxford, UK: Oxford University Press.