Project Summary (ITR). Computationally-Enhanced Construction Kits: Integrating Tangible and Computational Media for Construction and Design

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Construction kits—toys designed for the building or assembly of physical models—have historically played a powerful educational role in children's lives. Viewing the landscape of these kits—geometric design sets, erector sets, architectural blocks, anatomical models, chemical modeling kits, and so forth—we can see manifest strengths: at their best, they permit children to design and build three-dimensional models and to learn through tactile experience. Nonetheless, traditional construction kits also have striking limitations. They offer little in the way of direct communication with their users—for example, a traditional kit cannot offer a student information or advice about how to proceed in building a model, and as a result, crucial opportunities for student reflection may be lost. Perhaps even more importantly, traditional constructions—i.e., the models produced—tend to be aesthetically and behaviorally limited. This proposal argues that through the use of embedded computation, pieces within a construction kit may communicate with each other, with desktop machines, and with their users; and overall, by integrating construction kits with computation, the educational power and expressiveness of these kits can be greatly increased.

Objectives and Intellectual Merit. This project will develop a wide variety of computationally-enhanced construction kits, focusing on scientific, mathematical, and engineering domains (such as solid geometry, molecular chemistry, architectural design, and anatomy). The work will address a range of foundational questions, prominently including:

[a] How to improve the technical design of such kits (by, for instance, exploring hardware and algorithmic strategies for communication between pieces);

[b] How to expand the scientific content of these kits (for example, “intelligent” molecular models might now be able to indicate bond strengths between neighboring atoms); and

[c] How to characterize the cognitive and educational benefits (if any) of such kits in promoting student reflection, increasing the content that students learn, and enhancing the affective and aesthetic power of particular constructions.

In addressing these questions, the PIs will use a strategy of comparative design: that is, they will systematically explore a variety of design alternatives, characterizing the strengths and weaknesses of each, and attempting to "map out" the overall design space for construction kits. (Just to mention one example: there appear to be several broadly workable strategies by which construction pieces may communicate with desktop machines, and each of these will be investigated.) They will also make the design of construction kits the subject matter of undergraduate- and graduate-level courses at their respective institutions; and they will assess their designs (with K-12 student volunteers) through a combination of subject testing, observations, and interviews.

Broader Impact of Work. The goals and subject matter of this proposal are capable of profound and widespread impact in the promotion of American science and mathematics education. First, the history of construction kits strongly suggests that these kits often have a central affective role in developing students' interests in science and mathematics. Moreover, the advent of affordable materials for embedded computation—in combination with both powerful software applications and the World Wide Web—enables these kits to have a vastly more democratized and educationally potent role. For example, since desktop machines can now communicate with constructions, students can share information about (and sometimes even the control of) their constructions with large, extended social communities. This in turn offers the ability for new social structures to develop around physical constructional media; and these new structures could prove especially powerful in attracting traditionally underserved populations (including, but not limited to, women, minorities, immigrant students, and students in remote rural areas) into scientific and technological careers.
2. Project Description
Construction kits—toys designed for the building or assembly of physical models—have a venerable place in the history of education. Perhaps the earliest well-known example is “Locke’s blocks”, a set of children’s alphabet blocks popularized by the seventeenth-century philosopher John Locke [Sutton-Smith 1986, p. 119]. In America, building blocks were recommended to parents in 1826 as a toy to teach “gentle manners” to young children; and by the late 1860’s, Charles Crandall’s “tongue-and-groove” interlocking blocks had achieved a popularity that foreshadowed the later success of systems such as Lego. [Cross 1997] Such kits could apparently be quite extensive: the Museum of the City of New York has in its collection “a log-cabin construction set of nearly one hundred pieces dating from the 1850s.”[Harley 1990, p. 6]

In the past century, the landscape of educational construction kits has blossomed in a variety of directions. Building blocks of various sorts remain a dominant feature of that landscape; but in addition, one might include geometric and polyhedral kits (such as the gorgeous Zometool), engineering and erector sets (such as the sets popularized by the great American entrepreneur A.C. Gilbert [Watson 2002]), kits of malleable pieces (such as “Toobers and Zots”), plastic models for assembly (e.g., anatomical models, or scale models of airplanes or cars), chemical modeling sets, and many others. Historically, there is a strong argument to be made that such kits have had a powerful affective role in promoting students’ interests in science, mathematics, and technology; often, when interviewed, adult scientists trace their earliest sense of scientific enchantment back to work with construction kits of various sorts. The physicist Roger Penrose, for instance, recalls, “I did do things like make models—polyhedra and so on. They were usually geometrical models, which I made out of cardboard.”[Lightman and Brawer 1990, p. 417] The astronomer Margaret Geller likewise recalls “toys where you could connect flat shapes up with rubber bands to make solid figures”, and credits these toys with developing her own highly refined abilities for 3D visualization. [Lightman and Brawer 1990, p.361] The physicist John Wheeler, according to an interview [Csikszentmihalyi 1996, pp. 52], “remembers being interested in ‘toy mechanisms, things that would shoot rubber bands, Tinkertoys, toy railroads...’” The architect Frank Lloyd Wright reportedly traced his design skills back to his early childhood experiences with the building blocks (known as "gifts") associated with the German educator Friedrich Froebel. [Brosterman 1997] It is not hard to find other, similar recollections among technologists and scientists (there are many interesting remembrances, for example, regarding erector sets to be found in Watson [2002]).

Collectively, these reflections suggest that there are clear—if perhaps hard to quantify—strengths of construction kits in the larger landscape of educational artifacts. Unlike (for example) material conveyed via text or computer screen, constructed models provide tactile, as well as visual, input for their creator: a polyhedral or molecular model held in the hands affords a kinesthetic perception of three-dimensional structure that is arguably difficult to achieve by other means—even including the impressive techniques provided by virtual-reality systems. (Such considerations—relating to the role of tactile perception in education—have likewise long been central to research surrounding the use of “manipulatives” in mathematical instruction. (Cf. [Ball 1992], [Hall 1998], [Chao, Stigler, and Woodward 2000].) In their role as physical artifacts, construction kits can provide the young builder with a natural introduction to the behavior of materials—and to considerations such as friction, stability, and modular design. Beyond these explicitly intellectual or cognitive considerations, there are also intriguing social affordances of construction kits: the kits inhabit a social realm of educational (but not heavy-handedly "school-like") play. They offer unforced opportunities for collaborative learning: several builders can work together on distinct individual constructions, or on a single project. When completed, constructions and assembled models are often put on display in homes and classrooms, where they can serve as a spur for curiosity or discussion—and perhaps just as important, where they
can serve as a source of pride in craftsmanship for their creator.

On the other hand, there are also limitations (pedagogical and otherwise) to traditionally-conceived construction kits. For example, the educational content of construction kits is in general rather obliquely conveyed. A student who builds a molecular model may well have no idea whether her constructed object corresponds to a real (or possible) compound; a child constructing a polyhedron with a geometric kit may well have little opportunity to “see” any interesting structure or symmetry in the object that he has built. (Indeed, Margaret Geller’s earlier-mentioned positive experiences with geometric kits crucially depended—in her telling—on the conversations that she had about her constructions with her father, a professional crystallographer.) Cognitive research in students’ understanding of scientific material underscores the benefits provided by periods of “self-explanation”—essentially, reflective pauses in which students can consciously address questions that they have about the material and their own learning processes. [Chi and Van Lehn, 1991; Chi et al. 1994] Arguably, traditional construction kits are at their weakest in promoting just such “self-explanation” episodes (particularly those kits, like geometric or chemical sets, in which the student may create unpredictably complex structures); a student who has built all or part of a particularly rich construction may not notice the content inherent in her construction, and thus may deem the result ordinary or uninteresting.

In short, then, construction kits provide little in the way of direct communication to their users; and as a result, many opportunities for exploration or reflection could conceivably be lost. And there are still other intellectual limitations as well. Typical construction kits can only convey a partial representation of their intended subject matter. Molecular models show a molecule’s gross structure, for instance, but not more subtle features such as bond strength or the distribution of electrical charge (nothing in a typical model of water, for example, suggests the strong dipole moment of the molecule). Similarly, anatomical models cannot adequately show the means by which nerve signals are conducted, or the means by which a bird’s wings provide lift.

And just as construction kits have social affordances, they likewise have peculiar social weaknesses. Most construction kits are (at least in our opinion) aesthetically rather sterile and limited. Beyond the thin gruel of painting models, there are few opportunities for aesthetic elaboration or personalization: for instance, a child cannot actually design or customize her own construction pieces. The result is that, once constructed, even a model or project for display always seems to carry a certain sad muted note of stifled creativity. One might hope that finished constructions could have rich possibilities as interactive display objects; but most assembled constructions—whether anatomical models, geometric solids, or mechanical toys—tend to have extremely limited behavioral repertoires (with a few notable exceptions, such as robotic Lego constructions). Moreover, if a child does not have the luxury of a particularly supportive community of interest, there may be little in the way of an “audience” for her constructions; a young girl, for instance, may find herself without local women colleagues with whom to share insights and enthusiasm about her projects. (Watson’s history of the erector set [2002] describes several poignant scenarios of this kind.)

By considering both strengths and weaknesses of construction kits, then, we may arrive at several fundamental insights about how computational media could be beneficially integrated with these kits. By and large, the technological notion underlying these insights is that the individual pieces of construction kits may be augmented with small, embedded, individual computers, and that the act of “linking” construction pieces may also correspond to enabling communication between their respective computers. This is of course a non-trivial technological assumption to make, but it is by no means unachievable, as later sections will argue. For the remainder of this section, we will outline the goals and methods of our proposed work.
We propose to develop a wide variety of *computationally-enhanced construction kits*, focusing on scientific, mathematical, and engineering domains (such as solid geometry, molecular chemistry, architectural design, and anatomy). These kits are intended to retain the traditional strengths of construction kits—their emphasis on tactile design, their (occasionally beautiful) evocation of subject matter, and their affective power for children—while addressing the educational and cognitive concerns mentioned above. Moreover, in creating these kits, we plan to address a range of foundational research questions, prominently including:

[a] How do we improve and systematize the *technical design* of such kits? (For instance, there are a variety of strategies by which construction pieces can communicate with each other and with desktop systems. How do we make informed engineering choices among these alternative strategies?)

[b] How do we expand the *scientific content* of these kits, and what technical and interface problems need to be addressed in doing so? (For instance, if we wish to represent bond strengths between neighboring atoms in chemical models, how accurate and informative can these representations possibly be? Or—to take another example—how might we best convey three-dimensional symmetry operations to a student constructing a geometric model?)

[c] How do we characterize the *cognitive and educational benefits* (if any) of such kits in promoting student reflection, increasing the content that students learn, and enhancing the affective and aesthetic power of particular constructions? (We might ask whether, for instance, computationally-enhanced kits can in fact promote self-explanation among students, and—if so—whether “self-explanation” takes the same productive form in this sort of activity as it does in more traditional text-based activities. Or, to take another example, we might employ novel output devices or software applications to permit students to customize their constructions; we could then investigate whether this activity has any measurable affective or motivational benefit regarding the student’s attitudes toward scientific construction.

In addressing these questions, we will use a strategy of *comparative design*: that is, we will systematically explore a variety of design alternatives, characterizing the strengths and weaknesses of each, and attempting to “map out” the overall design space for construction kits. (Just to mention one example: there appear to be several broadly workable strategies by which construction pieces may communicate with desktop machines, and each of these will be investigated.) We will also make the design of construction kits the subject matter of *undergraduate- and graduate-level courses* at our respective institutions; and we will *extensively and energetically assess* our designs (with K-12 student volunteers) through a combination of subject testing, observations, and interviews.

The remainder of this proposal will elaborate on the ideas introduced above. The following (third) section summarizes our own work in previous relevant NSF-sponsored projects. The fourth section discusses our proposed research in greater detail, and places this research in the context of current related work at other institutions. Finally, we discuss some remaining potential problems and pitfalls in this research; and we include a timetable for our proposed work.

3. Previous Related Work

*Note: Current NSF grants for both PIs are attached separately.*

**Relevant prior NSF Research Grants (Eisenberg).**

As Principal Investigator

National Science Foundation Young Investigator Award, August 1992-1997. (Award # IRI-9258684.) This is a five-year award for $25K/yr from NSF; in addition NSF matches up to $37.5K/yr of corporate support. [Total awarded: $282K/5 yrs (sum of $125K in "baseline" funds and $157K in matching funds).]
As Co-Principal Investigator


The primary contributions of the PI to these grants centered around the themes of creating design environments for children; investigating the role of end-user programming in application design; integrating computational and craft activities; and creating "computationally-enriched" physical objects and artifacts for education by endowing craft objects with embedded, end-user-programmable computers. For the purposes of this proposal, summaries of current and recent research may be surveyed through the following websites, as well as through the references listed in the biographical summaries appended to this project.

For craft technology work: www.cs.colorado.edu/~ctg/
Home page of the PI: www.cs.colorado.edu/~duck/

Relevant prior NSF Research Grants (Gross).
As Principal Investigator
“Back of an Envelope an Architecture for Knowledge Based Design Environments” — National Science Foundation Grant (IIS-96-19856 and IIS-00-96138: $320,000) to explore and demonstrate a recognition-based system architecture for freehand drawing as an interface to design application programs. (1997-2000) The result of this work was a software framework ("back of an envelope") that recognizes freehand-drawn diagrams in 2-D (e.g., architectural diagrams) and links them with relevant domain knowledge (for example, simulated behavior)—much as we propose to do here in 3D with computationally-enhanced construction kits.

“Avoiding Conflicts in Subsystem Layout in Architectural Design: a constraint based approach” — National Science Foundation (Grant DMII-93-13186: $140,000) to demonstrate the application of constraint based CAD in systematizing the layout of building components (1993-1995). This work resulted in the “Construction Kit Builder” software, described in the paper “Why can’t CAD be more like Lego?” In the software, a designer creates and then works with two-dimensional CAD models in which the components have built-in assembly and placement rules.

Home page of Mark D Gross: http://faculty.washington.edu/mdgross
The Design Machine Group page: http://dmg.caup.washington.edu

Institutional Support.
For this proposal, Gross and Eisenberg will be able to make extensive use of the many institutional resources available to them. Eisenberg is a member of the Computer Science Department, as well as the Center for Lifelong Learning and Design (G. Fischer, director), and the Institute of Cognitive Science (W. Kintsch, director) at the University of Colorado, Boulder. Gross is a member of University of Washington’s Department of Architecture, where he directs the Design Machine Group; and adjunct in the Department of Computer Science and Engineering; he also serves as Ph.D. program faculty in Educational Technology. The architecture students (at the UW) are a special resource for this project; they bring a focused interest and set of skills in crafting physical materials (e.g., wood, metal, plastic work) and designing physical artifacts for functional and aesthetic performance. The University of Washington is home to the Center for Engineering Learning and Technology (CELT), directed by Professor Cynthia Atman; we plan to draw on this Center’s expertise in designing and evaluating our construction kit prototypes in teaching undergraduate engineering courses.
4. Research Themes and Goals
In this section, we elaborate on the research goals and methods introduced in Section 2 earlier.

4.1 Design
Textbooks and other learning media can provide information and teach analysis; construction kits—perhaps uniquely—offer a venue for learning design. Consider, for example, a Schaum outline book on basic electricity: it succinctly conveys principles of electric circuits and offers dozens of supporting problems (and solutions) in circuit analysis. Notably, however, it contains not a single design problem, presumably because for any problem in design there may be several or even dozens of legitimate solutions. In contrast, an electric circuit kit—such as the kind sold by Radio Shack—does provide a set of circuit components that can be assembled into various designs. However, this sort of kit typically comes with a book of specific projects to be built by carefully (and often mindlessly) following a circuit diagram. We propose that computationally enhanced construction kits offer a rich space of learning environments between these extremes (the book of solved analysis problems and the kit of pre-digested projects).

4.2 Specific areas of “computational enhancement” for construction kits
We believe that there are specific, identifiable, and achievable areas in which “computational enhancement” of construction kits can be accomplished. These areas are: [a] communication of digital information between linked pieces, [b] communication between (partial or whole) constructions and desktop systems, [c] communication between constructions and users, and [d] computational means for enhancing the behavioral range or aesthetic quality of constructions. We briefly describe each of these areas in turn.

Communication between linked or neighboring construction elements. One of the major purposes of embedding computation within individual construction pieces is to permit those pieces to communicate amongst themselves. It is this capability that permits a collection of pieces to identify patterns of connection within a complete or partial construction. For instance: by having each “atomic” piece in a molecular model communicate with the pieces to which it is linked by a bond, each piece can, by straightforward algorithmic means, determine the overall molecular structure in which it has been placed. Likewise, a set of architectural blocks could determine whether they have been arranged in an arch; a set of bones in an anatomical model could determine whether they have been correctly placed; and so forth. The ability of an overall construction to identify patterns of connection among its pieces is fundamental to the techniques described in the following two paragraphs.

Communication between construction kits and desktop machines. By endowing construction pieces with the ability to communicate, we likewise enable overall constructions to communicate with desktop machines. To pursue the example mentioned earlier: a chemistry student might thus be able to link a newly-constructed molecular model to her desktop machine and receive information about the construction that she has made (e.g., whether this is a common or even chemically feasible molecule). Likewise, a child who has built a polyhedron might receive specific advice or suggestions from a desktop application about how to visualize symmetry operations in the structure that he has built. In general, the computational power of desktop applications (and, by extension, the World Wide Web) may in this way be brought to bear upon a student’s physical constructions.

Communication between constructions and the user. Once construction pieces have been augmented by computation, it should be feasible to augment them with additional means of
identifying or expressing their “current state” to the user. This might be accomplished via means as simple as a flashing light or two, or as complex as an embedded LCD screen. Again, to continue our previous example: a molecule of water might have some means of expressing the electronic distribution of the overall construction by (e.g.) differentially shading the individual atoms of hydrogen and oxygen. Similarly, two nodes of a constructed polyhedron might “light up” simultaneously to indicate that they are interchanged under a particular symmetry operation. Construction pieces might likewise be regarded as potential input devices: turning the previous example around, a student might (e.g.) query whether two polyhedral nodes are equivalent under a symmetry operation by pressing or squeezing them simultaneously. In general, then, the development of “user interfaces” for educational construction kits—interfaces that include visual, aural, and tactile input and output—constitutes fertile ground for the computational enhancement of these kits.

Greater expressive range of pieces and materials. Finally, there are numerous avenues by which we can expand the creative possibilities of construction kits themselves through computational means. Construction pieces can be endowed with simple dynamic capabilities (e.g., one could make a building block that expands and contracts rhythmically along a single dimension). An especially powerful means of expanding the expressive range of pieces would be to permit them to be programmable, in the manner of the programmable Lego brick. [Resnick et al., 1996] It should likewise be possible, with the advent of output devices that “print” in wood or plastic, to permit children to design and decorate their own customized construction pieces, thereby moving construction kits significantly further in the direction of personalized artistic media.[Eisenberg 2002, Gershenfeld 1999]

These four areas of “computational enhancement” constitute the foundational themes for our proposed design work. But within each of these four areas, there are alternative design methods to explore. For instance, communication between construction pieces can take place through a variety of means (touch, light, electrical sockets, and sound, to name a few); and some distinguished pieces may be endowed with more “central” (or complex) processing capabilities than others. Likewise, there are a variety of means by which constructions can communicate with a desktop machine. One possibility is to have a dedicated construction piece that connects directly to the computer (a solution reminiscent of the “interface crickets” employed by Resnick’s group at the MIT Media Lab in creating the programmable Lego brick). Another possibility—employed in delightful examples by Ishii’s group at the Media Lab [Ishii and Ullmer 1997], and also in our own “Tangible MouseHaus Table” (to be described below)—is to use the desktop machine to identify (e.g., via cameras or sensors) a construction, which may or may not have its own embedded computers. One major goal of our work will be to investigate these alternatives and to develop a body of comparative lore (or perhaps a set of design rubrics) to further the engineering of next-generation construction kits. This in turn implies that we will not simply create isolated examples of construction kits, but will develop prototypes with an eye toward highlighting and comparing distinct design solutions to the problem of construction kit creation; and this comparative outlook will also form the basis of our course materials (described in section 4.5 below).

4.3 Previous Prototypes; and Candidates for Implementation Under This Proposal

Our students and we have developed several prototypes of construction kits in our respective laboratories. Though small in scale, these prototypes have been sufficiently encouraging to spark our enthusiasm for the more systematic and larger-scale research described in this proposal. We begin by briefly describing these previous prototypes, and then turn to plausible candidate construction kits to be designed under this proposal.
Navigational Blocks [Camarata et al. 2002] are a set of wooden blocks developed as part of Kenneth Camarata’s Master of Architecture thesis at the University of Washington. Each block contains an orientation sensor, a microprocessor with an infrared communication link, and electromagnets. The blocks, (each representing one of “who”, “when”, “where”, etc.) were originally designed as a ‘tourist kiosk’ interface to a database of historical information. The user configures the blocks to pose queries, which are transmitted via IR to a desktop computer with the database, and the results then displayed on a screen. Electromagnets mounted on the sides of the blocks offer haptic feedback as to the query’s validity. The hardware and software of the blocks is not limited to this tourist kiosk application: we have used the blocks to interact with other domains as well, including simple music, media, and the control of home environments.

Speech-Enabled Alphabet Blocks [Eisenberg et al. 2002] are a set of blocks created by K. Kaowthumrong, N. Lee, and W. Lovett as a class project undertaken at the University of Colorado under the supervision of M. Eisenberg. These are a set of blocks whose sides are labeled with letters; each block is equipped with an individual embedded computer (the “cricket” programmable brick developed at the MIT Media Lab). Adjacent blocks communicate with each other via fiber optic links, and touch sensors are used to distinguish the orientation of each block on a table. When a series of blocks is placed side-by-side, each block communicates its top-face letter to the next; a final (distinguished) block then communicates the entire series of letters to a desktop speech system, which pronounces the resulting word (assuming, that is, that the blocks’
top surfaces do in fact spell a word).

In the Tangible MouseHaus Table project built by Gross’s students at the University of Washington [Huang, Do, and Gross 2003], an urban designer configures the built elements of an urban plaza, using colored paper to represent built and park areas. A video camera makes a photograph of the configuration, which is parsed and then passed to a pedestrian simulation running on a desktop computer. The system projects a display of resulting pedestrian flows dynamically onto the physical model to inform the designer of the effects of his or her proposed configuration. This example, then, represents a form of computationally-enhanced construction in which the pieces themselves do not feature embedded computation; but the setting in which they are placed nonetheless permits these pieces to communicate with a desktop system.

In our own work, these examples have represented tentative—but highly exciting—first steps; the prototypes serve to illustrate both the technical challenges and (for us) the remarkable and still-untapped educational potential of computationally-enhanced construction and design. In the remainder of this subsection, we outline several plausible candidates for implementation in this proposal, representing a range of scientific, mathematical, and engineering domains, and suggesting the wide scope of design strategies available for the creation of novel construction kits.

Chemistry: Molecular modeling. Perhaps the most widely-employed of all scientific construction media is in the realm of chemistry; even in the current era of high-performance graphics, most undergraduate chemistry students still find that molecular models are an indispensable (if occasionally frustratingly uninformative) tool for developing their own skills of spatial visualization. We believe that chemical modeling represents a particularly fertile area for exploring the themes described in this proposal (indeed, many of the sample scenarios mentioned in passing thus far have been drawn from this domain). Consider, then, a chemical modeling set in which the pieces representing atoms are each equipped with an embedded computer providing (at the least) the chemical identity of each individual piece. With this basic enhancement, a newly-constructed molecular model could “know” its identity, and communicate that identity to a desktop application. Thus, a student who has constructed a model of (say) formaldehyde can bring that model to her desktop machine for identification; the desktop system can propose relevant exercises (e.g., to describe the symmetry of the molecule created); and the student can then receive suggestions for relating her model to other chemical structures (e.g., the system could point the student to natural succeeding sample molecules such as acetaldehyde or acetone). A more advanced student could be presented with spectrographic data regarding the molecule, and shown how the various features in the spectrum are related to particular sites in (or characteristics of) the physical model. In effect, then, the coupling of mutually communicating pieces and a desktop machine permits the design of substantially more educationally rich and potent chemical kits—kits that encourage the “self-explanation” episodes mentioned earlier—but that nonetheless retain the advantages of tactile and physical design.

An enhanced chemical construction kit also affords us the opportunity to explore a deeper or more informative representation of domain concepts. For example, if the atomic pieces are equipped with some means of representing their local state—perhaps as simple as a light of varying intensity, or a set of lights providing a color code—then a kit could indicate (e.g.) the electron density associated with a particular atom within a molecule. (To take an example: a hydrogen atom connected to an oxygen atom in a model of water would have a slightly positive charge relative to the oxygen atom; this would of course not be the case were the hydrogen to be part of a simple H2 molecule.) More broadly, in designing a computationally-enhanced chemical modeling kit, we can explore the possibility of representing information that crucially depends on
an atom “knowing” what molecule it occupies; this includes such notions as bond strength, stereochemical notions (e.g., whether two atoms are equivalent under some symmetry of the overall molecule), whether an atom is part of a larger identifiable “group” (e.g., whether a hydrogen atom is part of a methyl CH3 group which is itself part of a larger molecule), and so forth. In working toward the representation of this sort of information, we have the opportunity of expanding not only the educational but also the potential advanced or professional uses of chemical modeling sets.

Mathematics: Geometric Modeling. Among commercial construction kits for education, three-dimensional geometric kits such as Zometool and Polydrons are especially prominent and well-supported by additional curricular materials; kits of this type permit children to build a wide range of geometric solids, including (but of course not limited to) “classical” shapes such as the five regular (or Platonic) solids. We feel that there are several potentially powerful (not to mention fascinating) ways in which computational media could enhance the design of such kits. One possibility is to embed small computers and LED lights within spherical pieces representing the vertices of solids; the edges connecting neighboring vertices would serve to connect the associated computers. (The actual engineering of interlocking vertices and edges would be delicate, but the Zometool design of “connectors” and “struts” represents one of a variety of plausible solutions to this problem.) The resulting construction kit would allow students to construct polyhedra with remarkably rich possibilities for behavior. A set of vertices occupying a single plane could “light up” in unison to reveal interesting patterns or symmetries within the solid (see [Holden 1971] for many examples along these lines); or sets of vertices equivalent under some symmetry operation could light together. More playfully, one could imagine polyhedra in which the vertices light up in interesting programmatic patterns (e.g., according to rules of connectivity much like the cells in Conway’s “game of life”[Gardner 1985]); or the solid could be the source of “Simon-“like spatial visualization games in which the student attempts to follow and memorize patterns of moving lights in three dimensions. In this respect, computation could introduce still greater aesthetic richness to an already-beautiful activity.

Computationally-enriched geometric kits would (much like the molecular modeling sets) benefit from communication between desktop machines and physical constructions. A desktop system could reveal to the student interesting relationships between a particular construction and others (e.g., once a student has built an icosahedron, the desktop system could suggest that the student look at its dual, the dodecahedron, or perhaps at the marvelous truncated icosahedron, or “soccer ball”). In a similar vein, the desktop system could propose spatial visualization exercises to accompany some physical manipulation of the newly-constructed solid. And, looking to the fourth (aesthetic/behavioral) dimension of computational enhancement, geometric construction provides natural paths to explore as well. Just to take a particular example, one could employ dynamic elements in polyhedral construction to make shapes that change their designs over time (several commercial mathematical puzzles, such as “Alexander’s Star”, make use of such construction techniques); or one could explore such advanced topics as hinged dissections of solids (i.e., dissections of solids into pieces that can be smoothly rearranged into other solids[cf. Frederickson, 2002]).

Biology: Anatomical models. There are numerous commercial kits through which students can construct models of (e.g.) the human heart, eye, or skeleton (as well as models of animal physiology as well). We believe that these models are, as educational artifacts go, distressingly limited precisely along the lines discussed in the second section of this proposal. In general, these models provide only a model of structure, not function: once a plastic eye (say) has been assembled, the student has little or no information about how the various parts function together—how the eye muscles behave, how light is actually focused on the retinal surface, what
A young student truly interested in medicine or biology is likely to find such a construction kit relatively tame and disappointing. We believe that by endowing elements in such models with computational control, it should be possible to create anatomical models that include a far wider range of dynamical behavior, and a far greater degree of informative accuracy, than has been possible heretofore. A model of the eye (to pursue the example) could be equipped with controls that permit the student to shift the muscles of the eye; it could include light sensors on the retinal surface to permit the student to explore (and graph) how light intensity varies along that surface under different internal and environmental conditions; it could include controllable parameters representing “malfunctions” of various sorts, to show the physiological basis of nearsightedness or macular degeneration.

Note that such a “computationally-enhanced anatomical model” shares some of the technical features of the chemical and geometric kits mentioned earlier: in each of these cases, construction pieces are designed to communicate with each other, with desktop machines, and with the user. (For instance, in the case of the eye model as described, muscle elements would presumably communicate with each other; light intensity on the retinal surface could be communicated to a desktop system for graphing; and the student could interact with parameters representing the thickness of the eye’s lens.) There are interesting differences, however, between this type of construction kit and those mentioned earlier: unlike chemical or geometric kits, which are intended to create wide (or really, unlimited) ranges of artifacts, anatomical models are among a class of “specialized” model kits whose purpose is to create a single item. In the context of this proposal, what this distinction implies is that a single-purpose kit has a relatively identifiable pedagogical mission. Thus, the computational tools that accompany such a kit can be devised around a rather crisply defined curriculum, and the behavior of the model can be made consistent with a particular “real-world” system. At the same time, such kits do not lend themselves especially well to aesthetic enhancement (as in the case of geometric models) or to arbitrarily complex constructions in need of identification (as in the case of chemical models).

The above-mentioned examples (and domains) represent several plausible design projects to be undertaken in this work. These do not by any means represent the only prototypes planned. Other possibilities include (e.g.) devising novel construction elements, with user-programmed behaviors, for incorporation into mechanical models and automata; devising building blocks with interesting dynamical behaviors (e.g., blocks that expand and contract rhythmically, or that rock back and forth); construction kits that employ optical devices (such as lenses and mirrors), light sensors, and computer-controlled light sources; construction kits based on recursive L-system designs with which students can “print out” and create physical models of complex botanical structures; and so forth. We believe that a wide range of prototypes can be developed, in large part because the prototyping activity will be the focus of courses taught at our respective institutions (see section 4.5 below); thus, moderate- to large-scale student projects will be a source of representative prototypes for further development.

4.4 Related Work

The work described in this proposal is influenced by (and indebted to) a number of related efforts in combining tangible and computational media. The work of Mitchel Resnick’s group at the MIT Media Lab (both in the creation of the programmable Lego brick and in the design of a range of “digital manipulatives”[Resnick et al. 1998]) likewise combines the notions of physical construction media and educational objectives. Other work in the design of computational construction kits includes the ActiveCube project in Japan [Kitamura et al. 2001], the work of P. Wyeth and G. Wyeth [2001] in creating “tangible programming elements” from Lego Duplo pieces, and the computational blocks of Anderson et al. [1999]; likewise, the playful triangular-tile building set described in Gorbet, Orth, and Ishii [1998] can be viewed as a set of mutually-
communicating blocks for creating a variety of three-dimensional structures. More generally, the work described here can be seen as part of a larger (and continually burgeoning) tradition in the field of embedded and ubiquitous computing [Gershenfeld 1999, Hansmann et al. 2001]; and there is a particularly strong affinity between this work and the design of physical interfaces (see, especially, Greenberg and Fitchett’s [2001] work on “phidgets”, a class of end-user-programmable physical devices that interface with application software).

The work proposed here differs from these previous efforts in several fundamental respects. First, our goal is not to focus on a single example or design paradigm (as in the programmable brick or ActiveCube projects), but instead to work from a framework of comparative design. That is, a major goal of this work is to produce an illustratively wide range of prototypes, and thereby develop a thorough taxonomy and vocabulary—a body of professional lore—for the design of computationally-enhanced kits. We prefer to see this work as the seed of a new, teachable engineering discipline for educational designers, rather than as a basis for a single exemplar or commercial product. Second, this work places strong emphasis on domain-specific construction kits for science, engineering, and mathematics (e.g., for domains such as chemistry and geometry). This in turn enables us to address issues such as the enhancement of scientific domain content (an issue that is less prominent in most other projects, and that has been little addressed by the ubiquitous computing community generally). Third, we propose to design artifacts to address specific cognitive and educational issues (such as the enhancement of students’ reflection and self-explanation, or the effectiveness of computationally-enhanced construction kits at conveying basic or advanced domain concepts). Finally, our work places an explicit focus on aesthetic (and affective) issues, exploring means for enhancing the expressiveness of construction kits (e.g., through computationally-enabled decoration or output tools). This is in especially stark contrast to (e.g.) projects based upon the use of Lego or plain cubical blocks.

4.5 Implementation and Assessment of Kits

Equipment and Laboratory Resources Requested in This Proposal. The resources that we are requesting for this proposal include two graduate-level students at each of the participating institutions (for a total of four), and fabrication equipment (such as three-dimensional printers, and low-power laser cutters) to facilitate the construction of prototypes. The laboratory equipment will also be used within our design courses, as described in the following paragraphs.

Undergraduate/Graduate Design Courses as “Seedbeds” for Our Work. We plan to develop various prototypes not only in our own research laboratories but also in the context of two extremely well-received project-based design courses that we have taught at our respective institutions. We intend to further develop these courses not only so that students can work on construction-kit-oriented projects, but also so that we can build a true curriculum around the design and engineering of such kits.

To briefly describe our current course efforts:

• The Design Machine Group at the University of Washington has for two years offered an extraordinarily successful interdisciplinary workshop studio class in "physical computing"—design, engineering, and construction of computationally enhanced physical artifacts and environments. [Camarata, Gross, and Do 2002] This workshop brings students with diverse backgrounds together to work on projects that integrate computational abilities in objects and places: embedded, wearable, ubiquitous, or pervasive computation. Through project work they explore materials, mechanics, electronics, software, and the aesthetic component of design.
The course introduces an initial palette of components (PC, Handyboard, stepping and DC motors, nitinol wire, light, and temperature sensors) but each design team employs whatever materials it needs to achieve its goals. Project teams involve undergraduates, graduate students, and staff from art, architecture, computer science, electrical engineering, informatics, music, and technical communication. Each brings a different professional perspective and experiences; each takes away a different set of new skills. The resulting projects are clever, creative, and offbeat; yet all involve serious engineering and technology skills. The studio Web site is at http://courses.washington.edu/arch498z

• At the University of Colorado, the course “Things that Think” (first offered in 1997, and now in its fifth iteration) focuses on the creation of new types of physical artifacts for science education—including mechanical toys, construction kits, science exhibits, and so forth. Like the University of Washington course, Things that Think is offered to both undergraduates and graduate students (and has included students from a variety of engineering disciplines, psychology, and architecture, as well as computer science); and like its counterpart, Things that Think introduces students to a variety of components and materials (focusing for the most part on the “cricket” programmable bricks from MIT, and the use of a laser cutter and mechanical tools for physical construction). The current course web site (with links to the sites for previous iterations of the course) is at: http://www.cs.colorado.edu/~ctg/classes/ttt2003/

Pilot Testing and Assessment with K-12 Students Starting in the second year of the proposed research, and continuing through the final year, we will conduct extensive and varied assessment of our prototype construction kits with K-12 students whom we will recruit as volunteers from the local (Boulder) school system. The age levels of the students recruited will be dependent upon the particular domain of the construction materials involved: for instance, the chemical modeling kit and anatomical modeling kit would be most reasonably employed with middle and high school students, while the geometric modeling set would be employed with students as young as fourth or fifth grades. Assessment will be conducted to answer a variety of questions, including (but not limited to) the following:

• What aspects of the subject domains are encountered by students using these kits? How do these kits compare, in their coverage of subject matter, to traditional construction kits drawn from the same domain? (Techniques to be employed here include videotaped work sessions and structured interviews with students.)

• What do pre- and post-tests (based in the relevant subject matter) reveal about the development of students’ skills or concepts as a result of working with these kits? (Techniques here include the use of subject-material tests, as well as tests for potential general areas of transfer such as—in the example case of geometric kits—spatial visualization. Pre- and post-interviews will focus on the development of students’ language—e.g., their vocabulary, descriptive clarity, and accuracy—in discussing constructions or models. Videotaped work sessions could also be used here to study the development of concepts, as in the provocative papers collected in [Granott and Parziale, 2002].)

• How do we characterize the patterns of usage (e.g., the time spent on construction vs. reflection) exhibited by students employing these kits? (Techniques here include videotaped work sessions and interviews—the latter focusing on whether students employ or reflect upon constructions outside the structured laboratory setting.)

• What can we say about the affective or motivational role of these kits, particularly as
compared with both traditional kits and with other age-related educational/recreational activities such as video games? (Techniques will include both structured and informal interviews.)

Role of Collaborative Consultants. We have secured agreements from four first-rate scholars to collaborate with us in designing and assessing our prototype construction kits, to help us in the development of curricular ideas and material for our design courses, and to contribute to our theoretical understanding of the role of physical/computational materials in education generally. These collaborative consultants are:

Prof. Andrea diSessa (University of California, Berkeley) is a member of the National Academy of Education, author of Changing Minds: Computers, Learning and Literacy (2000) and (with Harold Abelson) Turtle Geometry (1981). Prof. diSessa’s research interests include the development of conceptual understanding in physics, the use of computational media in science learning, and motivational aspects of children’s learning in science.

Website for Berkeley Graduate School of Education faculty:
http://www-gse.berkeley.edu/faculty/gsefaculty.dg.html

Prof. Susan Finger (Carnegie-Mellon University) is on the faculty in the Civil and Environmental Engineering Department at CMU and co-editor of the Springer-Verlag journal Research in Engineering Design. Prof. Finger is also a member of the Rapid Design through Virtual and Physical Prototyping Project, and teaches a sophomore-level design course in this area; this course should provide numerous opportunities for students to work on construction-kit-related projects. Professor Finger’s home page: www-2.cs.cmu.edu/~sfinger/home.html

Rapid Design Through Virtual and Physical Prototyping Project:
http://www-2.cs.cmu.edu/~radproto/

Prof. Yasmin Kafai (UCLA) is in the division of Psychological Studies in Education at the UCLA Graduate School of Education and Information Studies. Her research focuses on the design and assessment of computer-rich learning activities and cultures. She is author of Minds in Play: Computer Game Design as a Context for Children’s Learning (1995) and has been appointed to the National Commission on Gender, Technology and Teaching.

Prof. Kafai’s home page: http://www.gseis.ucla.edu/faculty/kafai/

Andee Rubin (TERC, Cambridge, MA) is a Senior Scientist at TERC. Her research interests include the use of computational tools in mathematics education and issues of gender equity in technology. She is co-editor (with N. Yelland) of Ghosts in the Machine: Women's Voices in Research With Technology (2002), and co-author (with Chip Bruce) of Electronic Quills: A Situated Evaluation of Using Computers for Writing in Classrooms (1993).

Andee Rubin’s home page: http://www.cs.colorado.edu/~andeer/

We have attached letters of support from each of these consultants to this proposal.

Dissemination of Our Results and Ideas. A central goal of this work is to ensure widespread dissemination not only of our construction kit designs, but also of our evaluation and assessment methods and results, engineering techniques (including what does and doesn’t work in the creation of computationally-enhanced kits), and curricular materials. Indeed, part of the reason for our focus on “comparative design” in this proposal is that we do not wish to promote any one prototype or design paradigm, but rather to encourage the larger community of educational technologists to explore and experiment with the ideas behind our prototypes. Toward the end of
the period for our proposed research, we plan to sponsor a workshop or symposium of interested researchers in the design of computationally-enhanced physical artifacts for science and math education; we see this as an important step in building a (much-needed) larger community interested in these issues.

5. Potential Problems and Pitfalls
We conclude by noting several potential questions about this research, and our responses.

• If these kits are prototypes, how will they be disseminated to larger populations of students? We see this research as a crucial, but not final, step in the development of truly robust, large-scale computationally-enhanced kits. The purpose of this research is not to (e.g.) found or promote a commercial enterprise, but to spark the interest of a much wider community of scholars, educators, and developers. We believe that without a research effort of this kind, there is bound to be some occasional ad hoc commercial development of novel construction kits in the coming decade; but without the early, proactive participation of research scientists and educators, there will be little impetus for promoting experimental designs of such kits, and for assessing (and teaching to students) the range of engineering techniques possible. Our goal, then, is to use this research to build an intellectual community which, in relatively short time, will develop many more examples (and commercial products) than would otherwise be the case.

• How might these kits promote science learning among populations (e.g. women and minorities) historically underrepresented in the sciences and technology? Traditionally, the lack of attention to these issues (particularly gender equity issues) in the design of construction kits has been an embarrassment (cf. Watson[2002]). We intend to pay particular attention to those factors in the design of construction kits that influence motivation among “underrepresented” students. Our belief is that computationally-enhanced kits represent a potential democratizing force in the landscape of science education artifacts: for those students (for instance) for whom such kits seem dry or impersonal, the use of computational media to personalize, customize, decorate, or animate these kits may well be a significant motivating factor. Likewise, the ability of these kits to communicate with desktop machines affords us room to experiment with building larger Web-based “communities of interest” (and support) for these kits. For instance, a student who has created a particular chemical structure with the chemical modeling kit could use that structure to communicate a query to a larger community of interest in chemical modeling. Certain dynamic constructions (e.g., dynamic geometric models) might also be controlled remotely (cf. the “Telegarden” project [Goldberg et al.1996])

• What about larger-scale (e.g., full-classroom) assessment of the kits, beyond small-scale studies with K-12 volunteers? The research planned here is unlikely to develop the prototypes in sufficient quantity (or perhaps, of sufficient robustness) to warrant “large-scale” assessment efforts of this type. We believe that this level of assessment should be the focus of a later-term (and perhaps larger-scale) proposal, employing perhaps one or two kits developed in larger quantity.

6. Timetable
Year 1. Initial development of prototypes (beginning with the examples described in Section 4.3). Year 2. Continuing development of prototypes; first pilot tests with students. Year 3. Development of second round of prototypes; continuing pilot tests; dissemination of first full collection of curricular materials. Year 4. Development of second/third round; pilot tests; sponsorship of workshop/symposium. Year 5. Development of third/fourth round; pilot tests; second collection of curricular materials.

The design courses described in Section 4.5 will be offered in each of the five years of the proposed research.