The UCube: A Child-Friendly Device for Introductory Three-Dimensional Design

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ABSTRACT
Currently there is a burgeoning interest in three-dimensional construction and design: 3D printing and fabrication devices have—with almost shocking swiftness—become available to students and home hobbyists, allowing a vastly expanded audience to imagine, and then print out, their own tangible designs. Still, while the fabrication devices themselves are becoming available to younger children, the task of 3D design itself remains difficult for youngsters. The difficulty lies in the “2D screen bottleneck”: three-dimensional objects for printing must generally be designed in complex software that works exclusively with, and through, a flat two-dimensional screen. This paper introduces the UCube, a spatial input device designed specifically with children and ”3D novices” in mind. The basic idea behind the UCube is that it provides a spatial, volumetric array of light switches that can be turned on and off individually by the user; the pattern of lights is then input to a desktop computer, where it can be employed to specify a collection of 3D points in space. The result is that 3D design—at least for simple shapes—becomes a matter of moving one's hands in space to (e.g.) select the boundary points of the desired shape. We describe the design of the UCube, the influences behind it, and some early encouraging pilot tests of the device with middle-school-age children.

Categories and Subject Descriptors
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General Terms
Human Factors

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UCube, Three-dimensional fabrication, Three-dimensional design, spatial cognition

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1. INTRODUCTION
Three-dimensional construction has, of late, become a source of tremendous excitement and innovation in human-computer interaction. In large part, this is due to technological improvements (and economies) in 3D-printing devices. A decade ago, only the wealthiest labs and corporations could afford to invest in a three-dimensional printer; but over the past several years, a burgeoning subculture of 3D-printing researchers and enthusiasts has developed, and supported, an expanding landscape of affordable, desktop fabrication devices. The Makerbot [21], for instance, is a kit of parts that can be assembled into a working 3D printing device; it sells for a little over $1K (an astonishing price by the standards of the previous decade), and prints out physical objects in plastic (Figure 1). While the Makerbot is perhaps the most dramatic example of newly-affordable 3D printing, there are a variety of efforts along similarly exciting lines. The Fab at Home project [8, 22] has also developed an inexpensive printer kit; and the RepRap project [10, 30] aims to make a desktop 3D printer capable of printing out the parts needed to construct yet another printer. Augmenting these efforts, there are commercial enterprises offering desktop printers (e.g., [6]) that are more expensive than the experimental kits, but far cheaper than a previous generation of printers. Moreover, the advances are not merely at the level of hardware, but also include a rapidly developing social infrastructure: for example, the website thingiverse.com allows users to download designs for printable objects, while services such as Shapeways [32] and Ponoko [29] permit users to send software specifications for tangible objects that can then be printed out and mailed back to the customer. The implications of this revolution in personalized construction are especially profound for education, and for children's activities more generally. As anticipated by Gershenfeld in his prescient book Fab [11], the advent of "fab labs" in schools, community tech centers, and garages has begun to enable young people to imagine and build a remarkable variety of physical "stuff". A recent paper by Lipson and Kurman [19] includes a thoughtful discussion on the subject; as the authors write, "Personal fabrication technologies provide a powerful educational tool that offers students the driver's seat in the design and engineering process.... Computers and low-cost, small-scale manufacturing technologies, when integrated into science and technology classes, help educators craft physical models to help demonstrate educational concepts." [p. 60] A position paper by Berry et al. [3] echoes this sentiment: "Taking a new concept from mind’s eye to physical form can be fulfilling and motivating. Young students typically have not had the opportunity to see their concepts make the trip from an initial conceptual idea to a final physical form...
The advent of personal fabrication can allow students this opportunity for the first time." Moreover, the possibilities of empowering children with fabrication devices, in our view, goes way beyond science and mathematics education, and indeed way beyond classroom and school settings alone. Children can print out (e.g.) customized game pieces, charm bracelet items, costume accessories, diorama figures, model railroad scenery, and myriad other personally meaningful objects. (Cf. [7])

Figure 1. The Makerbot 3D printer: an assembled kit from our own laboratory.

In brief, then, digital fabrication and 3D printing are poised to have a tremendous impact on the creative lives of children. Still, there are important roadblocks that impede the most optimistic scenarios for children's construction. In our view, the most important of these is the difficulty of specifying and designing a 3D form suitable for printing. Currently, the standard method by which a printable 3D object is designed is through the use of modeling software: Rhino [31], SolidWorks [34], and Google Sketchup [12] are several prominent examples. While software systems of this type are extremely powerful, they also present significant challenges for youngsters attempting to design even simple tangible shapes: such topics as virtual camera angles, extrusion, polygonal meshes, and so forth are daunting (and arguably unnecessary) for an introductory experience in 3D design. Moreover, even the most user-friendly design software (Sketchup might be a good candidate example) cannot escape the essential difficulty of representing a 3D shape on a two-dimensional screen. There is an essential mismatch between the three-dimensional intuitions of a child's movements in space and the rather formal procedures by which a spatial object is specified for presentation on a screen.

This paper describes a novel prototype device, designed and built in our laboratory, that aims to provide a more intuitive, bodily-grounded introduction to three-dimensional design for children. The UCube, as our device is called, is a platform with a grid-like array of sites on which a set of transparent "towers" can be placed.

Figure 2. The UCube platform. Here, four transparent towers have been placed in the platform; on each of these towers, two lights have been selected. The resulting eight points designate the corners of a cube in space. (The dimensions of the cube, in "platform units", are two-by-two-by-two: that is, each edge of the designated cube is two units long, where a "unit" is the distance between adjacent holes on the platform, or equivalently two adjacent lights on a chosen tower.)

Figure 2 shows a photograph of the device; here, four towers have been placed at four locations on the platform. (The current UCube, as shown in Figure 2, has a four-by-four array of available sites; thus, the photograph shows four of the maximal possible set of sixteen towers placed within the device.) Each tower is equipped with a set of equally-spaced light switches (our current prototype has four switches per tower); these switches can be individually turned on or off. Thus, by placing a set of towers on the device and turning on a particular set of lights within those towers, the user can specify a set of selected points in a spatial array. As implied by our description, the current UCube provides a four-by-four-by-four spatial array, for a total of 64 specifiable locations in space. In the photograph of Figure 2, each of the four placed towers has two of its locations switched on; the resulting eight points designate the corners of a cube. The entire UCube device is connected to a desktop computer; thus, it acts essentially as a "spatial input device". The locations specified by the switched-on lights can now be transmitted to three-dimensional display and modeling software on the desktop computer. Figure 3 shows the associated UCube software displaying, on the computer screen, the cube designated by the selected points in Figure 2.
This highly telegraphic description is given merely by way of introduction. To anticpate: we believe that the UCube represents a potentially fertile (if still early) step toward providing tasteful, "body-centric" means for introducing spatial concepts and three-dimensional modeling to children as young as elementary-school age. The remainder of this paper is a more extensive unpacking of this argument. The second (following) section focuses on the operation and design of the UCube and its associated software; in this section we present a representative scenario for employing the device in the context of three-dimensional modeling. The third section presents the results of our first (still admittedly preliminary) pilot tests of the device with middle school children. The final section of the paper discusses related work, and the various influences behind the design of the UCube; we also use this occasion to explore the possibilities of the device for teaching and assessing spatial cognition in children. The section concludes with a discussion of ongoing and future work related both to the device itself and to three-dimensional construction by children more generally.

2. THE UCUBE: ITS DESIGN AND OPERATION

As a first step in discussing the UCube's role in spatial design–and in discussing the broader issue of children's three-dimensional design–this section is devoted to a more thorough description of our current device and its operation.

To begin with an overview, then: the UCube system is the combination of two elements: the physical input device of "towers" placed on a board, and the companion display software. These two systems work together to take the embodied actions of the user and display corresponding points and shapes on the computer. A sense of the scale of the device can be inferred from Figure 4, which shows a photograph of a middle-school student holding a newly-placed tower in the UCube platform while pointing simultaneously at the desktop computer screen beside it.

This photograph–which we will also return to in the discussion of pilot testing in a later section–reflects the essential nature of interaction with the device: points are designated in a spatial region provided by the platform, and then represented in real time on the computer screen. Thus, the UCube promotes an attention to the correspondence between the selected spatial points above the platform and the (more abstract) representation on the computer screen.

2.1 Hardware

The physical system for our first UCube prototype, as outlined earlier, consists of a platform with a four-by-four grid of potential sites, each of which can hold one tower with four switches, thus describing a 4x4x4 array of 64 potential points (see Figure 2).

The platform structure consists of three different horizontal "layers". The top (or upper surface) layer has a four-by-four grid of circular holes, into which the towers fit snugly. This layer acts as a brace to hold the towers upright, and ensures that they are resistant to being knocked over. The next layer holds the headers, which allow the towers to "plug in". Wires from the headers go down to the bottom layer, which hold the breadboard and microcontroller. The platform and towers are made of transparent acrylic, the side paneling of basswood. The switches are LED-backlit when active, making it more apparent which points are active as well as giving a more accessible "gestalt" of the shape being modeled. It also allows for some potentially interesting applications in dimly-lit circumstances, such as modeling constellations in a classroom or planetarium: in these situations, the lights of the selected spatial points stand out especially vividly.

Each tower connects to the platform through a six-pin header (power, ground, and four switches). The switch connections are then routed through a breadboard to a microcontroller (an Arduino Mega[1]). The Arduino is then able to communicate the active switches (and corresponding coordinates) to the computer through a USB cable. Figure 5 depicts a schematic diagram of the UCube hardware.
2.2 The UCube Software System

Our software makes use of the Processing[14] framework to read in the active coordinates from the Arduino microcontroller connected to the platform; the software then displays these as larger red points on a grid of grey dots. Users can rotate the grid along any axis by clicking and dragging with the mouse. In our current early prototype, there are only two buttons on the user interface: (i) an “export” button, responsible for taking the current set of active points and exporting them into "STL" file format (suitable for 3D printers), and (ii) a “mode” button which toggles between showing just the red dots as points and filling in an area (defined by a convex hull algorithm) to give a sense of shape.

The software interface is intentionally minimal in order to encourage the user to focus on the physical interaction. We felt it was crucial not to fall into the trap of making another software tool for experts, so the main purpose of the software is to act as an aid--a means to cognitively clarify and confirm the user's intentions. Although it is likely that we will extend the software somewhat in future iterations, our goal is to support the physical experience of specifying a three-dimensional object, and not to add functionality beyond what is necessary or helpful to that end.

2.3 A Sample UCube Scenario

As a sample scenario, imagine that we wish to create a triangular prism solid employing the UCube. We can begin this process by selecting three points to form a triangle, as shown in Figure 6; then, by placing two more towers and creating the same triangular shape "shifted over" by two units (Figure 7) we create the entire prism. Naturally, there might be many alternative pathways to forming the same eventual shape: for example, we might begin by placing four (or more) towers in the platform, and then experiment or fiddle with the chosen lights to approach the eventual goal of creating our prism. Alternatively, we might begin without any towers in the device at all: by placing our hands or fingers above the device, roughly indicating where the prism should be, we might then use our imagined locations as "guides", helping us to place the necessary towers in the platform and select the correct lights for the vertices of the prism.

In any event, having designed the prism using the UCube platform, and having checked that it looks like the correct shape on the computer screen, the final step is to export the shape into a format suitable for 3D printer output. The UCube software, as noted earlier, includes a feature for doing just this; and finally, we print out the prism, as shown in Figure 8.¹

![Figure 5. A schematic diagram of the UCube's design, as described at greater length in the accompanying text.](image)

**Figure 5.** A schematic diagram of the UCube's design, as described at greater length in the accompanying text.

![Figure 6. The first step in constructing our triangular prism: here, we create a planar triangular shape toward the left side of the platform, and can see the resulting shape on the computer screen shown at right.](image)

**Figure 6.** The first step in constructing our triangular prism: here, we create a planar triangular shape toward the left side of the platform, and can see the resulting shape on the computer screen shown at right.

![Figure 7. Completing the triangular prism. Here, we have added a second ("shifted") version of our original triangle to produce the six vertices needed to form the prism.](image)

**Figure 7.** Completing the triangular prism. Here, we have added a second ("shifted") version of our original triangle to produce the six vertices needed to form the prism.

¹ A video of the UCube in operation can be seen at: http://www.youtube.com/watch?v=W2W2o9Xr_h0
2.4 Limitations of the UCube

It will probably not have escaped the reader's notice that the UCube, as a three-dimensional modeling device, has significant limitations. To take the most glaring of these: the user can only model those shapes whose vertices are among the sixty-four locations accessible from the device. Moreover, those available locations are evenly spaced in the form of a three-dimensional grid, or lattice; thus, there are numerous simple-but-interesting shapes (such as the regular dodecahedron, composed of regular pentagonal faces) that cannot be designed in the current version of the UCube. Likewise, shapes with curved surfaces (such as a cylinder), demanding at the very least a high resolution of accessible points, could not be modeled in the current UCube. We will return to these issues in the final section of the paper, in the discussion of ongoing and future work.

3. PILOT TESTING

3.1 Procedure

Early in 2011, we conducted an initial (and informal) pilot test of the UCube with a group of 12-14 year olds. Fourteen participants, consisting of five girls and nine boys, were divided into six groups (five groups of two, one group of four). Participants were asked to model a sequence of five shapes of increasing complexity using the UCube along with the companion software. The target shapes were displayed on one half of a computer screen, while the UCube software showing the live model was displayed on the other half (Figure 9).

The first shape that participants were asked to model was a straight vertical line; after this, the requested shapes were a diagonal line, a cube, a triangular prism, and finally an irregular polyhedral object. No shape required more than four towers to complete, and shapes were always presented in the same order.

Participants were instructed to place the poles on the board (but not shown how), and were told that the software model could be rotated and filled in using the keyboard and mouse, should that help them complete the task. The participants were not given any hints as to how to complete the shapes and were not told when they had the correct configuration (they had to indicate their belief that the model was done). Participants were also instructed to 'think aloud' about their actions. The main purpose of the pilot study was to get an initial impression of how the UCube would act as an accessible 3D modeling tool–how well it could help "3D novices" overcome the "2D bottleneck".

3.2 Results and Discussion

Of the six groups who participated, four groups successfully modeled all five shapes, one group ran out of time after three shapes, and one group finished one shape. Sessions lasted between 17 and 30 minutes.

A variety of problem-solving strategies were observed during testing, as the participants tended to treat the exercise as a sort of puzzle to be solved. Simple methods equivalent to "try and see" were common, and seemed to serve as a base point from which to draw conclusions about the relationship between the 3D model and 2D on-screen representation (e.g. “No, not there, up one”). More sophisticated strategies were also observed—“deconstructing” more complex shapes into smaller, easier-to-model shapes (e.g. thinking of one side of a cube as a square) was observed from several groups. Another popular technique was to systematically match the on-screen perspective from the live model with the shape they were attempting to model (e.g. “Okay, first let's do the top view, and then go from the side”). By orienting the two models similarly, participants were able to make more accurate modeling decisions as well as check their model against the on-screen shape. Counting distance in terms of spaces on the board, between switches, or between dots on the screen was also a very common technique of reasoning about and describing position. For example, by counting that two vertices of a shape were separated by “two dots over and one down” on the screen, subjects were able to count the distance out on the physical UCube board. A few of the more mathematically-advanced participants used terms such as “axis” and “origin” to orient themselves and describe various positions on the board to their partners.

Another revealing observation in the pilot study was that, in the few instances of mechanical failure (certain switches not lighting up, towers not plugging in properly, or points not showing up on screen) the participants were still able (with a high degree of certainty) to complete the assigned tasks. This appears to indicate that, as opposed to arbitrarily moving the towers around until the two sides of the computer screen looked the same, participants had formed a more substantial mental model of the relationship between the UCube interface and the 2D representations on the screen. That opens the possibility that by performing the embodied interactions necessary to operate the UCube,
participants had actually strengthened their understanding of how 3-dimensional space is typically represented on a 2D screen. Although further testing and observation is needed, this finding would strengthen the argument for using the UCube in an educational setting to improve understanding of 3D space, as well as providing a gateway for youngsters to move on to more complex modeling software.

While the variety of problem-solving techniques we witnessed is a testament to the participants' ingenuity, it is also indicative of the fact that parts of the UCube are not immediately intuitive. While none of the participants had trouble understanding how to place the towers on the platform, the positions of the towers and switches had to be reasoned out explicitly. It was common for groups to clear the board of any poles when starting a new shape, even in cases where an overlap of points or tower positions existed. (Figure 4, for example–shown earlier in the context of explaining the UCube's operation–depicts one of the students placing a tower and checking the screen to see whether the tower placement is appropriate.) Although most groups completed all the shapes (or ran out of time), there were some expressions along the way of the difficulty of the task (e.g. “This is hard”, or “This is like a puzzle”). This indicates that design changes can be made in future iterations to help clarify the correspondence between positions on the UCube platform and the on-screen representation; for example, labeling the both the physical and software grid with a simple alphanumeric system.

Despite these drawbacks as well as the inherent limitations of the UCube design, these early results indicate a promising ability of youngsters to effectively engage with the UCube interface. In fact, despite various levels of success in completing the assigned tasks, the vast majority of participants exhibited a high level of engagement with the UCube. For example, although the group that completed only one shape seemed unmotivated to attempt to model the other shapes, they continued to play with the interface and observe the results, even stating “this is fun” and “I like the switches”. Participants also saw potential uses for the UCube outside of the specific exercise we assigned. Comments (unsolicited) included, “you should use this to teach geometry” and “you could make this a puzzle game”.

At the very least, these early results indicate that the majority of participants were able to take a 2-dimensional representation on the screen and model its 3-dimensional equivalent using the UCube, a very encouraging result in our eyes.

4. REFLECTIONS AND PLANS

Having described both the design of our device and initial pilot tests, we can now "step back" and take stock of the implications of this (admittedly still early) work. In this section, we discuss the research traditions that have influenced the design of UCube; we use the device as a springboard for exploring broader technological questions in education for spatial and three-dimensional thinking; and we discuss ongoing and potential future work involving the UCube and its likely successors.

4.1 Related Work

There are several strands of research that have strongly influenced the design (and motivation) for the UCube. Perhaps the most fundamental of these is in the area of "embodied mathematics"—that is, the notion that mathematical thinking and learning are affected by, and perhaps grounded in, metaphors derived from bodily experience. The most thorough and discursive (though largely theoretical) discussion of these ideas is in the foundational text by Lakoff and Nuñez [18]; the authors discuss physically-derived metaphors that underlie such essential mathematical ideas as numbers, operations, and sets. Such notions of embodied mathematics have—even before the Lakoff/Nuñez text—played a role in discussions of the development or instruction of mathematical ideas. The link between physical experience and mathematical growth was a strong element, for instance, in Montessori’s work (see, e.g., [15]); much of the motivation behind traditional mathematical "manipulatives" such as number rods and balance beams can also be traced to this intellectual tradition. More recently, theoretical discussions of embodied cognition have given rise to fine-grained observations of the connections between bodily activity and mathematical learning: Goldin-Meadow [13], for instance, describes a fascinating line of research in which children's nonverbal gestures appear to both reflect and, in some cases, anticipate their verbal understanding of concepts such as conservation and "inverse operations".

Pedagogical research in embodied mathematics has, moreover, proceeded hand-in-hand with the development of desktop, embedded, or portable technological artifacts to support the link between bodily actions and mathematical conceptualization. Papert's discussions of the Logo computer language [27] reveal this connection early in the history of children's computing: Papert discussed, for example, the way in which the program for a Logo circle resonated with children's bodily understanding of moving in a circular path. More recently, Nemirovsky et al. [25] describe the use of a computer-based motion detector system to assist children in the development of intuitions behind graphing; Howison et al. [17] used a device based on a Wii remote to assess children's understanding of ratio (the children attempt to move their arms in a manner illustrating a target ratio); Bakker et al. [2] created a collection of handheld objects ("MoSo Tangibles") with embedded sensors to help children learn about musical ideas via hand motions such as waving, squeezing (pressing hands together), and shaking up and down, among others; Mickelson and Ju [24] use sophisticated video and projection equipment as the basis of activities through which children can learn about mathematical ideas (e.g., symmetry, rotation angles) via large-scale physical movements.

The development of the UCube follows within this tradition, in that the device was created to enable children to specify and identify three-dimensional shapes by hand motions (instead of, by contrast, using symbolic commands directed at a two-dimensional screen display). At the same time, the UCube is not simply a device for mathematical instruction, but is more generally a tool for mathematical design. As noted at the outset of this paper, the intent of the UCube is to enable youngsters not only to learn about but also to build mathematical shapes.

Specifically, we see the device as part of a larger, burgeoning "technological ecosystem" around the activity of three-dimensional printing. The first section of this paper noted several prominent researchers who argue for the democratization of this technology, and for its applications to education. Indeed, exciting early work has been done in applying 3D printing to education in fields such as architecture [4], solid geometry [16], and mechanical design [20]. The UCube is designed so that it can be employed by younger students—younger, for instance, than the typical (undergraduate-age) architecture student. At the same time, we see no reason at all why the device could not be used by adult or professional-level students—particularly if (as we
argument: the form of a highly condensed (and necessarily telegraphic) treatment of spatial cognition, several points are worth making in device itself. While this is not the occasion for an extended device in this fashion, one can position this work as part of a tradition (dating back at least to Piaget [28]) in understanding spatial thinking and its development (cf. also [26] for a more recent treatment of the subject).

4.2 Technology for Spatial Education

The previous paragraph—referring as it does to the scientific study of spatial cognition—acts as something of a transition to broader topics of discussion, going beyond the particulars of the UCube device itself. While this is not the occasion for an extended treatment of spatial cognition, several points are worth making in the form of a highly condensed (and necessarily telegraphic) argument:

a. There is ample reason to believe that three-dimensional visualization—that is, being able to “think in 3D”—is an important component in numerous domains (engineering, architecture, chemistry, and geometry, just to name a few). For this reason, education within these domains needs to avail itself of means by which spatial thinking can be encouraged, promoted, and creatively exercised. (Cf. [9], [23], [33])

b. The previous point acknowledges the importance and value of 3D thinking and visualization: at the same time, it is worth noting that there is at least some evidence that these abilities can in fact be improved by appropriate experience. ([5]; [26], p. 208) In other words, 3D visualization abilities are not (like eye color) genetically unalterable, but rather—like many other cognitive abilities—capable of development and cultivation through motivated practice.

c. The creative possibilities of 3D thinking and design have exploded in the presence of high-resolution computer graphics, game devices, and (as we have argued) fabrication and design tools. Still, there is an unfortunate disconnect between the standard technological equipment available to children (in particular, the flat computer screen) and the intellectual challenge posed by 3D visualization. Put simply, it's hard to learn about three dimensions from an inherently two-dimensional representation. This accounts, in our view, for the continuing struggle to learn and use even well-designed 3D modeling software.

The upshot of this argument is that it is increasingly necessary to devise technological artifacts for spatial education—technological artifacts that take advantage of such innovations as embedded and wearable computing, GPS devices, volumetric displays, hand-held projectors, gesture recognition techniques, and many more. In other words, in order to provide children with rich, expressive spatial activities—activities that serve as meaningful connections to mathematics, science, art, and design—we need a technological ecosystem that extends far beyond the standard computer screen. Ideally, these novel technologies will not, however, act as "stand-alone" artifacts, separate from the rest of children's work; rather, they should be designed to interact with a range of other (more traditional) devices and activities. The UCube is an example of this tenet of design: it is not a self-contained plug-in toy for exercising spatial cognition, but rather is designed as an input device for a desktop computer, and as a connected element in the larger landscape of three-dimensional design and printing technologies.

We see the UCube, then, as one promising step within a larger agenda of educational design. Much as the term "media literacy" has come into vogue within educational circles, the notions of "spatial literacy" (or, along similar lines, "design/constructive literacy") will be both encouraged and rewarded by the advent of physical and material technologies beyond the screen. The time is arriving when children will routinely have the means for visualizing, designing, and printing such artifacts as mechanical toys, moving animal models, personalized computationally-enriched clothes and accessories, realistic historical scenery and costumes, and many, many more; but in order to achieve this vision we need to provide children, along the way, with the tools and techniques for mastering the spatial cognition that underlies this type of tangible design.

4.3 Next Steps: Ongoing and Future Work

It should be clear from our description in this paper that the UCube is still, as a technological artifact, in a relatively early stage: our current working prototype is still a bit fragile, and rather delicate to maintain. More broadly, there are many near-term improvements that we intend to explore, and that could enhance the operation and range of the device.

To begin with, it is interesting to consider the limitations in resolution of our current (four-by-four-by-four) device. In our next prototype, our intention is to increase the number of available points to 216 (six-by-six-by-six); in doing so, however, we need to consider the overall size of the device. While it would be desirable on the grounds of resolution to increase the number of points (and therefore towers) in the UCube device, if the device is too large it may be difficult for younger children to employ (e.g., their arms may not reach from the front of the device to all desired points); or, if we attempt to remedy this problem by "shrinking" the overall dimensions of the device, then it may become difficult to navigate one's hands between adjacent towers. In short, the physical constraints of a device such as the UCube make for subtle trade-offs in design—we want to provide more geometric expressiveness to the device while keeping it accessible to younger users.

There are still other hardware-level additions and improvements to make to the device. At present, for example, the UCube lights are in one color (red) only; it would be desirable to extend the range of the device by incorporating multi-color LEDs. This would enable children to (for instance) specify two simultaneous intersecting shapes within the device, one designated by blue lights and another by red; or one might use the color of the lights to communicate color information (or other semantically useful information) to the UCube software.
A more ambitious prospect is to augment the current UCube design so that the user can designate points that are not limited to the "integer lattice" implied by the current prototype. For example—as noted earlier—it is not possible to create a regular pentagon (and therefore a dodecahedron) in our UCube lattice. One possible direction to explore, then, would be a means to select a UCube position (as in the current version), but then to "adjust" that position geometrically from its starting point. Conceivably, a UCube light could be engineered so that it could be adjusted to a position in space within some (small) radius of its standard position; this would enable the user to create a vast range of shapes unattainable by the current system (though admittedly at the potential cost of a greater complexity of operation). In any event, overcoming the geometric limitations of the current lattice arrangement of points is a central problem for future development of the device.

These first suggestions—greater resolution, multiple colors, adjustable light positions—all refer to the hardware design of the device. In a complementary vein, there are a variety of software improvements (or at least experiments) to attempt. In the examples discussed within this paper, the default scenario has been one in which the user (student) has been trying to create a closed solid. Nonetheless, there is nothing about the design of the UCube that limits it to interpret points as constituting a surface. One might, for example, devise activities in which spatial points designate birds in a flock, insects in a (small!) swarm, or separate positions in a crystal lattice: in other words, the UCube can be employed to specify separate points in space, without having to interpret those points as elements of a larger solid. Yet another possibility is to keep track of the order in which lights are selected (a feature that the current software already implicitly includes), and to employ the UCube to specify a sequence of temporal positions in space—that is, a path. As an extension of this last idea, one might create spline curves on the computer screen by using the sequence of UCube points to specify a series of positions in 3-space; this would be one way of employing the UCube to introduce ideas of curved paths via physical movement.

Yet another possibility would be to employ the UCube as source of input to some existing (and extensible) commercial 3D software system: conceivably, the device could then be treated as a sort of "training wheels" interface to more complex design systems. In this interpretation—perhaps more suitable to professional users than to students or young children—the user would eventually taper off her usage of the device (or discard it altogether) once it is no longer necessary to her work.

In sum, then, there are ample opportunities for improving and extending this initial prototype device. In the near term, more (and more formal) pilot tests UCube with children need to be done. We are now particularly interested—given the encouraging results with middle school students—to see whether the device can be used and understood by still younger children.

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[31] Rhino. [www.rhino3d.com](http://www.rhino3d.com)


[34] Solidworks. [www.solidworks.com](http://www.solidworks.com)