Devices for Embodied Fabrication

by

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A thesis submitted to the

Faculty of the Graduate School of the

University of Colorado in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

Department of Computer Science

2014

This thesis entitled:
Devices for Embodied Fabrication
written by Benjamin A. Leduc-Mills
has been approved for the Department of Computer Science

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Date

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

Leduc-Mills, Benjamin A. (Ph.D., Computer Science)

Devices for Embodied Fabrication

Thesis directed by Prof. Michael Eisenberg

Digital fabrication technologies are increasingly finding their way into educational spaces of all shapes and sizes. These new technologies (3D printers, laser cutters, etc.) afford opportunities for exploring these new ways of 'making' and how they may change the way we learn, explore, and play. Although there is much excitement surrounding the 'maker movement' - and 3D printing in particular - there has been little examination of how to introduce a younger audience to 3D printing in an empowering way. This proposal argues that tangible interfaces - as opposed to 2D screen-based media - can be designed not only to support spatial reasoning and mathematical intuitions in children by engaging them in exploratory modeling and play, but that these interfaces can act as a democratizing force by enabling children to create physical objects with digital fabrication devices. The proposed work presents a series of novel tangible input devices for enhancing mathematical and spatial reasoning in kids with a focus on generating output for 3D printing. We discuss related work, the status of the proposed work, additional improvements to be made, a timeline for completion, and a discussion of risks, limitations, and outcomes inherent in the proposal.

Dedication

To all of the fluffy kitties.

Acknowledgements

Here's where you acknowledge folks who helped. But keep it short, i.e., no more than one page, as required by the Grad School Specifications.

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Chapter 1

Introduction

A number of computer scientists, technologists, and educators have declared that the era of personal fabrication is upon us[10][46]. New devices aimed at increasing the ability of the individual to physically manufacture their own ideas are being released at breakneck speed. The cultural and technological shifts caused by this change are taking many forms, yet few technologies associated with the 'maker' movement have received as much attention as 3D printing - the ability (by various means) to digitally design and then print out physical 3-dimensional objects. Media outlets from Forbes[52] to The Economist[1] have extolled the disruptive and democratizing possibilities that 3D printing offers - at least as it affects the traditional manufacturing supply chain. Less examined has been how to introduce novices, specifically pre-teens and early adolescents, to 3D printing - and perhaps more importantly - discussing what (and how) they might learn by being exposed to it. While the variety of desktop 3D printers continues to increase and the cost of adding a 'fab lab' of digitally-based manufacturing tools in the home or classroom steadily declines, the types of interfaces by which children can easily and intuitively design and explore the capabilities of 3D printers still remains a barren landscape consisting primarily of software-only solutions. It is this landscape that we are interested in seeding, following the best practices in computational and cognitive science with particular attention to children-centered design.

To this end, we present a class of tangible user interfaces (TUIs) designed to scaffold a child's ability to design, explore, and play in three dimensions, with a particular focus on enabling output for 3D printing. Significant work has been done on two devices that allow users to specify points on a physical, interactive, volumetric interface that simultaneously displays active points in real-time on a computer. The software on the computer allows for certain modeling operations on the set of input points (e.g., taking the convex hull), as well as exporting shapes to stereolithography (.stl) format, the preferred format for 3D printing. We propose that these designs form a new class of tangible input devices, and present early work on a portable pop-up book building upon the ideas expressed in the two earlier designs. The rest of the paper proceeds as follows: discussion of related work, description of completed work, the proposed work, a timeline for completion, and concluding thoughts.

Chapter 2

Prototype Systems

Over the past several years we have been exploring various means of creating a child-friendly tangible user interface that would serve as an input device for exploring 3D modeling and digital fabrication. To this end, we have created three prototypes: the UCube, an initial proof-of-concept device, SnapCAD, a more expressive and study iteration of the UCube, and PopCAD a paper-based interface addressing several of the concerns raised by SnapCAD. These systems all communicate with versions of a companion software program running on desktop computer. This chapter describes these systems, the motivations behind their design, and the technical work involved in their creation.

2.1 UCube

The UCube represents our first attempt to create a cooperative system of hardware and software that encapsulated and combined our beliefs about embodied cognition and the importance of accessible digital fabrication. The idea for the UCube originally came from the attempt to create a "3D Geoboard". Figure 2.1 shows a rudimentary 2D geoboard consisting of a 3x3 grid of nails stuck into a wooden block. Simple geometries, such as the triangle shown in the referenced image, can be made by stretching rubber bands around some number of "pegs". The geoboard invites a kind of tangible, exploratory, and embodied play that (as we discuss in Chapter 3) promotes children's learning in powerful ways. The goal, then, was to capture the "gestalt" of the traditional 2-dimensional geoboard and extend it - into 3-dimensions, and with a computationally-enhanced interface that could translate physical modeling on a device into a software program that could display the input from the geoboard in a meaningful way.

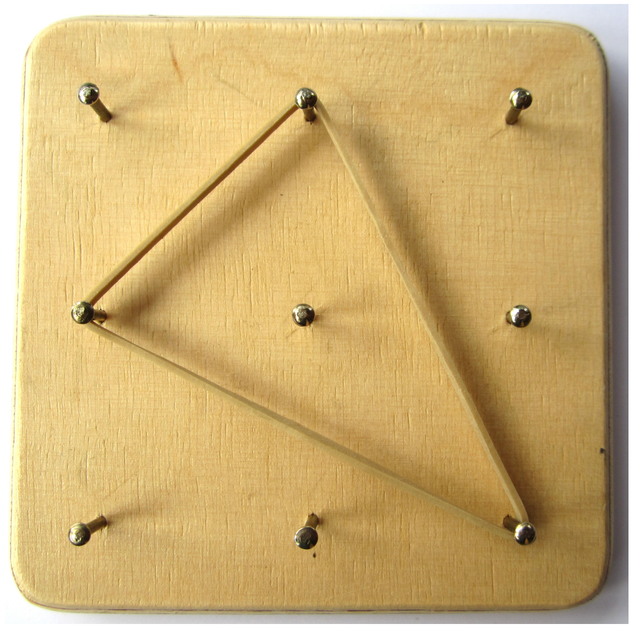


Figure 2.1: A simple 3x3 geoboard, with a rubber band stretched around several pegs, forming a triangle.

The UCube (as seen on the left in Figure 2.2) was the initial result of this goal. The physical interface consists of a set of vertical "towers" that are placed (and optionally re-placed) onto a board, acting somewhat like the nails in the 2D geoboard. These towers are moved around a grid of 4x4 evenly spaced nodes or sockets into which the towers are placed. The towers themselves contain four switches placed vertically along the tower, creating a potential for 64 (4x4x4) distinct points. Thus, when a tower is placed in a specific node on the board and a switch is flipped on, a particular (x,y,z) coordinate in three-dimensional space is activated and sent through a microcontroller to a piece of software on the computer. An abstracted illustration of the hardware system is seen on the right in Figure 2.2.

In turn, the UCube software takes the incoming coordinate data from the microcontroller and translates it into a real-time visualization on screen. The graphical user interface centers around a "ghosted" grid of all the potential points, with the active points being highlighted. In the first version of the software, the interface also provides a set of operations that can be performed on the set of active points in addition to normal scene manipulations like zoom and rotate. These functions include: taking the convex hull of the point set (as imagined in Figure 2.2), creating a sequential path or knot through the active points, exporting the convex hull or knot to .STL format for 3D printing, drawing a (non-printable) spline through the active points, saving and loading a shape, and editing the vertices of a convex hull via a click-and-drag interface (a more complete review of the software occurs later on in this chapter).

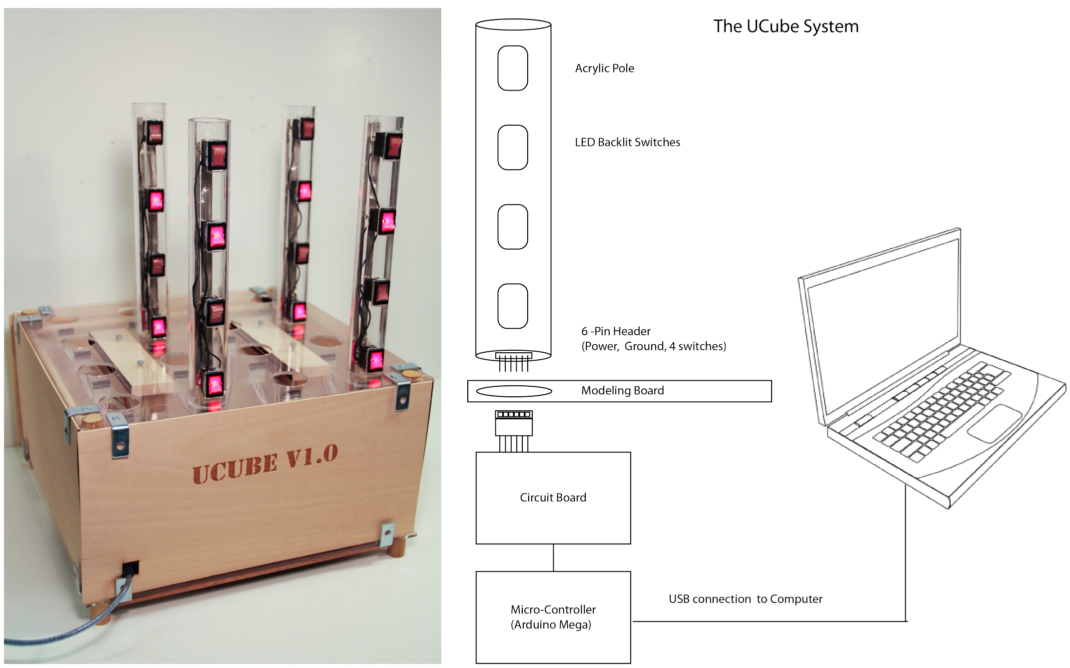


Figure 2.2: Left: The UCube device, with four towers and eight lit switches, representing the eight vertices of a cube. Right: a schematic illustration of the UCube hardware.

As a first step in discussing the UCube's role in spatial designand in discussing the broader issue of children's three-dimensional designthis section is devoted to a more thorough description of the UCube 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 2.3, 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 photographwhich we will also return to in the discussion of pilot testing in a later sectionreflects 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.

2.1.1 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. 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 of 1/4" thick laser-cut clear acrylic acts as a brace to hold the towers upright, and ensures that they are resistant to being knocked over. The next layer down holds the headers, which allow the towers to "plug in" and connect to the rest of the circuit. Wires from the headers go down to the bottom layer, which holds the breadboarded circuit and Arduino Mega microcontroller. The towers are made of transparent acrylic, the side paneling of basswood. The towers were laser-cut in order to house the four switches and corresponding circuitry elements. 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 (one pin each for power, ground, and four switches). The switch connections are then routed through a breadboard containing current limiting resistors for the LED switches to pins on a microcontroller (an Arduino Mega[81]). The Arduino is then able to communicate (via asynchronous serial communication) the active switches (and corresponding coordinates) to the computer through a USB cable. Figure 2.2(right) depicts a schematic diagram of the UCube hardware.

2.1.2 Limitations

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.

2.2 SnapCAD

Based on the feedback from these two user studies, a second, more powerful instantiation of the ideas from the UCube has been created. SnapCAD (formerly known as UCube v2) consists of a total input space of 7x7x7 points, forming 343 distinct coordinates. In our user studies with UCube v1, we noticed that users often encountered initial difficulties when required to 'find a middle' in the shape they were attempting to model, given an even number of total grid spaces. For example, to model a pyramid on on a 4x4x4 grid, one needs to construct a 3x3 subset of the 4x4 grid, using the middle point within the 3x3 set as the top of the pyramid. This influenced our decision to create an odd-numbered layout, creating a more 'natural' middle point in the hardware. The greater number of inputs vastly increases the expressive potential of SnapCAD (compared to the UCube) while still maintaining a manageable interface. Working on the scale of multiple hundreds of inputs necessitated the design of custom circuit boards to relay information effectively to the microcontroller. This change in scale also meant rewriting most of the modeling software to effectively handle the greater expressiveness of the physical system.

The use of conductive, magnetic snaps along towers constructed of custom-printed circuit board allow for more than one color of illumination, as different colored LED boards can be snapped onto any socket on the tower. This not only results in the ability to represent multiple shapes at once, but for the SnapCAD to become a platform for all manner of multi-player interactions (e.g. games, puzzles, shape matching contests), with each 'player' assigned a unique color. To this end, we have created a simple '3D Tic-Tac-Toe' implementation on the SnapCAD. Additional changes to the software include supporting multiple but separate convex hulls of different colors, the ability to create and export shapes created from the minimal spanning tree of a set of input points, and the ability to adjust the width of the segments in the knot/path and minimal spanning tree modes. The click-and-drag editing mode now includes the knot/sequential path and minimal spanning tree modes as well as the convex hull mode. We also adjusted the knot-forming algorithm to handle paths that cross or self-intersect, as well as providing a 'close knot' button to complete a circuit in a shape, allowing for even more kinds of 3D-printable objects. While significant work has been done to bring the UCube and SnapCAD to their current states, we believe not only that there is room for additional improvements to be made, but that, as opposed to focusing on a incremental but essentially similar interface as the subject of a thesis, it is far more intellectually interesting to focus on a class of objects that demonstrate multiple incarnations of a set of ideas.

2.3 PopCAD

Our motivations for creating alternative interfaces to the UCube and SnapCAD stem from the desire to explore this intellectual space more generally; it is far more interesting to discuss a **class** of tangible interfaces for scaffolding digital fabrication than it is to discuss a singular device. To this end, we looked at some of the weaknesses of SnapCAD and towards technologies we had yet to explore. While SnapCAD can admirably perform a number of modeling tasks, it was always envisioned as one device amongst an 'ecosystem' of next generation fabrication tools. It has strengths, but obvious weaknesses as well; in particular, the SnapCAD hardware was expensive to produce, and so would be a difficult proposition for some schools or fab labs; it is also rather unwieldy and unportable - it moderately heavy, fairly large, and has many separate pieces that could break or go missing. Thus, an interface with cheaper and more portable materials was desirable.

To address these issues we chose to build a pop-up book combining traditional paper-crafts and paper-friendly electronics such as copper tape. In recent years, revolutionary work has been done in combining electronics and paper crafting[96][82], leading to new techniques and new uses for traditional materials. Paper is inexpensive (especially when compared to circuit boards), light, and easily portable, making it an ideal material choice for a device that would not suffer the same limitations present in the SnapCAD. Although we often think of 'paper' as a rather static material, there are in fact many variations in the size, weight, color, transparency, and composition of contemporary paper products. For the initial prototype, we used a simple construction paper as it provided a balance between strength and flexibility as well as having a consistency well-suited to laser etching and cutting. The pop-up book (named PopCAD) has a 3x3x3 array of 27 points which are evenly spaced 3 inches apart on a 12" x 18" paper surface. The book folds on a single center crease making the closed footprint of the book roughly 12" x 9".

Each tower has a copper tape circuit consisting of three LEDs on the front face and three corresponding capacitive touch sensors on the left face. The copper tape acts as a paper-friendly conductive material to connect the electronic components together much like traditional wire. The LEDs are soldered onto the copper tape for greater stability. The capacitive sensors are simply a piece of copper tape which is connected to a pin on a microcontroller (in the first version, this is an Arduino Mega Pro). By bringing the internal pull-up resistor connected to the pin 'LOW' (to ground) and then timing how long it takes to get back to a 'HIGH' state we can tell if the connection is being influenced by a capacitive force. For example, if there is no interference on the circuit, the timer will normally only get to '1' before the resistor is back to a HIGH state; if a finger is placed on the copper tape, the reading will be much higher (typically around '17'). Based on this change, we can detect which switch was touched and toggle the associated LED on or off. The hollow interior of each paper tower is used to solder thin 30-gauge wire to the three LEDs, the three switches, and ground. These seven wires are soldered to a row of headers that stick through the bottom of the first layer of the pop-up book. Wires are then run along the backside of the top layer of paper from these headers to the microcontroller. The entire circuit in then encased in a cloth-covered cardboard binder that acts as a book cover as well as a means to protect and hide the electronics.

The software originally written for the UCube and SnapCAD was adapted to work with the pop-up book, making it capable of similar types of algorithmic modeling and stereolithography output for 3D printing. As the grid is 3x3x3, it also makes sense to adapt some of the game-playing aspects of the larger devices (e.g., it would still be possible to play 3D tic-tac-toe). In addition to adding this functionality, there are several improvements and finishing touches to be made on the book itself. Additionally, the current hardware setup for the pop-up book does not allow for the LED's to be snapped on or off, making certain multi-player or multi-shape operations impossible. Weather or not this functionality is crucial to the pop-up book will determine if changes need to be made.

Given the different medium of the pop-up book (paper as opposed to circuit boards), it is worth exploring the possibilities afforded by a cheaper, more flexible material. For instance, the flexibility of paper might provide the means for new types of modeling actions. It is plausible to imagine paper tabs or other mechanisms that perturb the LEDs off the integer lattice, or alter the overall topology in such a way that new shapes are possible (e.g. by deforming an equidistant grid into a spherical shape). There may be additional sensors or hardware that could be embedded into the book to provide new functionality (rotation, proximity, pressure). Additionally, due the inexpensive and portable nature of the pop-up book, it is worth exploring the sorts of interactions that could occur between several pop-up books (e.g., extending the input field to include two or more grids, networked interactions like cooperative modeling tasks, or competitive games like 3D-battleship). By using paper as a material to think with, we may find further possibilities as development continues.

2.4 Software

Put stuff about software development here. Details. Screenshots.

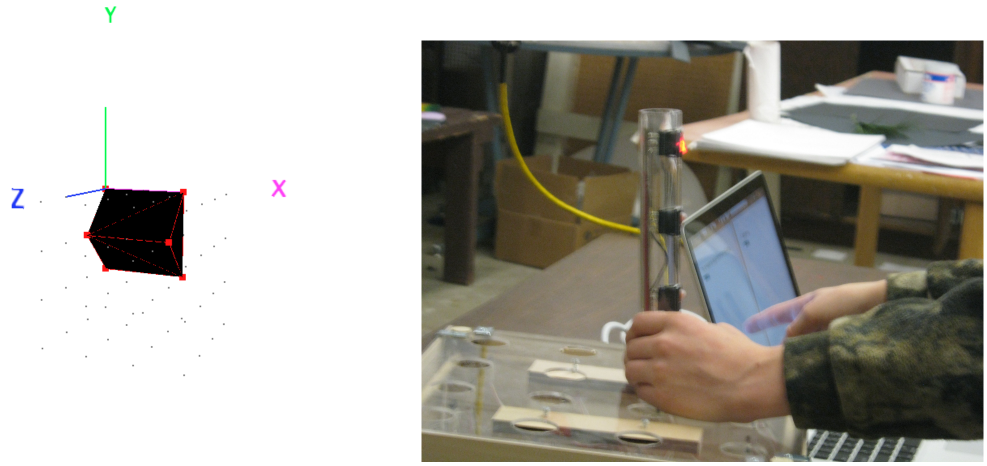


Figure 2.3: Left: a screenshot of the UCube v1 software, showing the triangular prism generated by performing the convex hull function on a set of 6 input points. Right: A photograph of a middle-school student using the UCube. Here, the student holds a tower in the platform and points simultaneously to the screen representation of the selected point on the desktop computer.

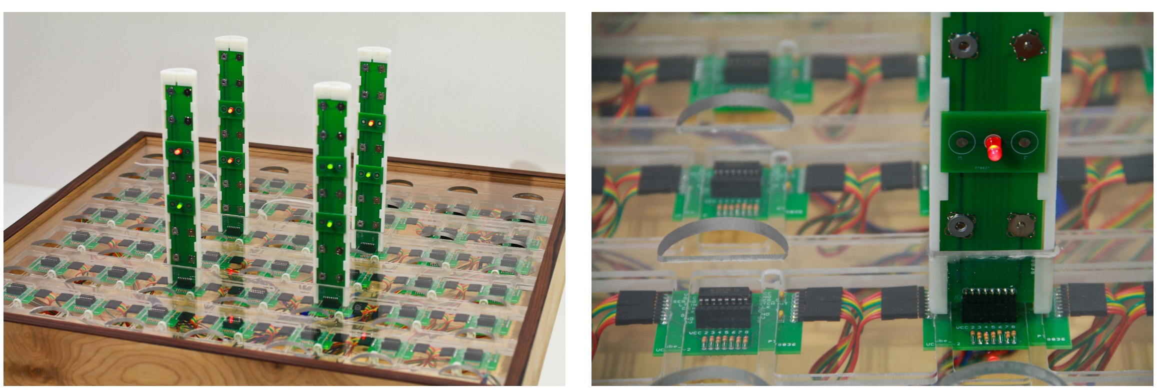


Figure 2.4: Left: the SnapCAD interface, showing the hardware configuration corresponding to the picture below in Figure 2.5. Right: a detail of the SnapCAD hardware - the PCB tower is housed in a 3D-printed shell, which plugs into a shift-register board. The LED boards snap on to the towers via magnetic snaps.

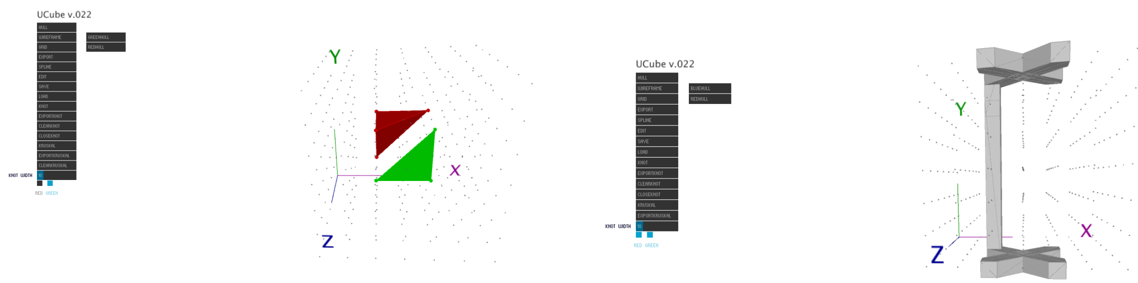


Figure 2.5: Left: The SnapCAD software showing two convex hulls of different colors. Right: the SnapCAD software showing a minimal spanning tree model.

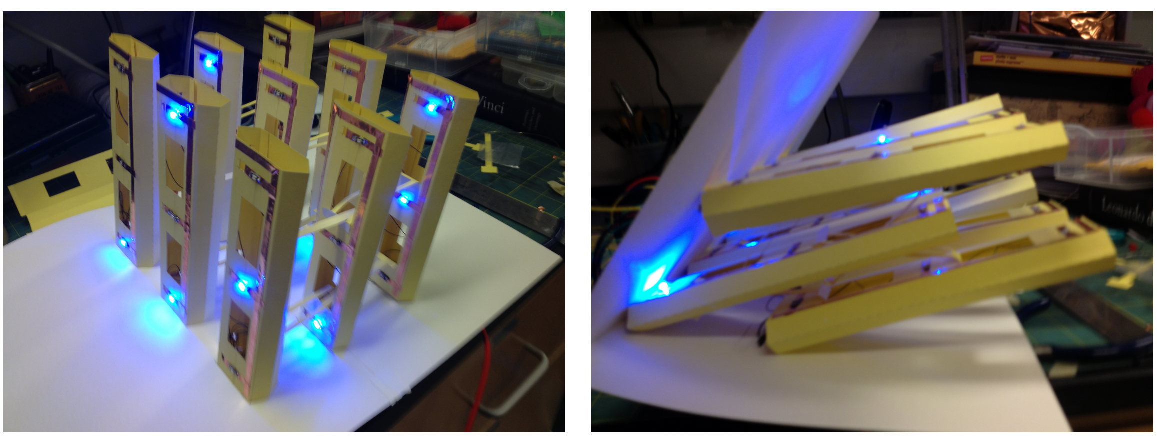


Figure 2.6: Two views of the pop-up book prototype, showing the paper towers and LEDs in both open and closed states.

Chapter 3

Related Work

The belief that tangible objects[1] play an important role in children's education is relatively recent. Friedrich Froebel's use of 20 wooden forms he dubbed 'gifts' in the first Kindergarten was in 1837[45]. It took until 1907 before an extension of Froebel's ideas and a focus on physical, manipulative objects and tasks was implemented by Maria Montessori in the first Casa Dei Bambini[84]. The interest in children's learning incorporating the use of manipulatives progressed steadily, most notably by Jean Piaget and his work on 'genetic epistemology'. Piaget wrote extensively on the stages of development during which certain kinds of knowledge emerged[60], including logical-mathematical knowledge related to the kind we wish to foster. Although Piaget's specific theories have been strongly challenged[114][100], his influence was extremely important. Seymour Papert, one of Piaget's intellectual descendants, published Mindstorms[91] in 1980 and with it introduced his own ideas about constructivism. Combined with the advent of the physical Logo turtle, Papert brought many constructivist ideas into the modern age and opened the door for a technical and cognitive exploration of how computation and interactive objects could be combined to examine the link between tangibles and children's learning.

While a rich and diverse lineage of tangible and embedded user interfaces has progressed since (and partially because of) Papert, the genealogy of the proposed work derives from an interest not only in constructivist-like activities, but in theories about how interaction with physical objects

[1] It is worth noting the difference in this work between 'tangible objects' of the sort that a child might play with (e.g. Lego) and 'tangible user interfaces' (TUIs) that a child might interact with - typically a peripheral device (apart from the keyboard and mouse) that communicates physical interactions to a computer.

may be beneficial to learning. In cognitive science, the area of embodied cognition examines the ways in which our interactions with the physical world shape our cognitive experiences from a body-centric point of view. More specifically, embodied cognition holds that our cognitive processes are 'deeply rooted in the body's interactions with the world'[122]. This is in stark contrast to decades of research in cognitive science wherein the mind was viewed as a sort of central but detached information processing unit where motor-sensory functions were more-or-less secondary inputs and outputs to a main system[29]. Although there are several different tenets of this body-centric view, the primary conclusion relevant to our proposal is that interactions with physical objects can shape, clarify, and reinforce our cognitive processes in scores of disparate areas. For example, Goldin-Meadow shows that through an analysis of hand gestures, one is able to predict a subject's 'readiness' to learn[48]; that is, the gestures they make while explaining a concept are literal clues as to the state of their cognitive processes. Of keen interest for this work in particular is a domain referred to as embodied mathematics. Lakoff and Nuñez[73] give a fascinating account of the origins of mathematics from an embodied point of view. They propose that humans, by virtue of their interactions with the physical world, inevitably form certain intuitions of a mathematical nature. Recognizing small numbers of objects (e.g. the pre-verbal ability to do arithmetic with less than five objects), estimation, and simple comparisons are a few of the examples given in[73]. From these basics, they argue that four kinds of physical operations (object collection, object construction, using a measuring stick, and movement along a path) form the basis of simple arithmetic. Although the book postulates about concepts as ungrounded and seemingly abstract as infinity, for our work it is enough to suggest that the interactions present in our designs follow from these four operations and may in fact contribute to the solidification of more complex mathematical ideas in 3D modeling and digital fabrication (e.g. forming correct mental models of 3-dimensional objects).

In their section on 'Thinking Through Doing', Klemmer et al.[70] give a particularly poignant summary of why we ought to consider the body as instrumental in any human-computer interaction design, stepping through many of the concepts outlined above. In fact, the marriage of ideas derived from Papert's work with the conclusions of embodied cognition are not new, and appear to substantiate our motivations to produce tangible, manipulative interfaces as opposed to purely 2-dimensional screen-based work. In the mid-to-late 1990's, research examining the ways in which physical objects might be infused with computational ability started to coalesce around several themes[37]. Resnick's work with 'digital manipulatives'[102][126] specifically references the contributions of Froebel and Montessori in the design of a series of 'programmable bricks' with computational ability whose aim is to make certain specific concepts (e.g. systems-level thinking) more salient for the user. Ishii's work on breaking down the divide between physical and virtual worlds into 'tangible bits'[63][62] has subsequently set the stage for a new family of tangible interface designs that support the kind of embodied interactions that our work seeks to produce. By constructing environments and artifacts that focus on the possible physical representations of computational components, these works (among others) created the philosophical space to delve into how tangible objects might affect users at a cognitive level. Our proposal is a confluence of both tangible and cognitive design; as Resnick states, 'We are interested in Things That Think only if they also serve as Things To Think With'[102].

Of particular interest for the current work are explorations focusing on 3D modeling and perception with tangible interfaces. Prime examples include software that allows for 3D shapes to be flattened into paper-printable, origami-esque polyhedra[38], a construction kit with kinetic memory so as to record and playback certain user-generated manipulations[99], as well as several variations of 'smart-cube' interfaces [117][108] that encourage spatial and logical reasoning in order to make use of the computational aspects of the cubes. While diverse in their implementation, these kits point to ways in which interface design can tease out the kind of 3-dimensional problem-solving and exploration present in the proposed work.

Related contributions focus more on the cognitive processes involved when exploring embodied interfaces with children. Research on supporting creative problem solving with children[19], arguing for a kindergarten-influenced approach to creative thinking [101], embodied approaches to analyzing children's interactions with smart objects[12], as well as the embodied design of interfaces for introducing mathematical concepts to kids[8] have shown a great degree of correlation between

Figure 3.1: Left: The ActiveCube system. Right: The Roblocks system.

physical interaction and learning in children.

Yet so far, there have been few attempts to design embodied interfaces for children that specifically address the growing presence and availability of digital fabrication tools. KidCAD[43], a deformable pad that captures the 2.5D geometry of depressions made on the underside of the surface, was a very promising idea in that it allowed very young children to take small objects from their surroundings (or their hands) and 'stamp' them into the pad - an intuitive and satisfying experience. Unfortunately, the authors intentions to be able to output the geometry to 3D printers has not yet manifested. Easigami[57] is a set of interchangeable and interlocking polyhedral faces with smart 'hinges' that can reproduce the morphology of a set of connected faces while connected to a computer. In contrast, Easigami **is** able to export this morphology to a stereolithography file ready for 3D printing. There are several other interfaces that deal with 'interactive fabrication'[121]; devices that manipulate materials interactively based on various input from a user, such as controlling a laser cutter with a laser pointer (instead of through a CAD program)[87], or a wearable device that takes in a CAD file and provides haptic feedback to make the physical creation of the device by hand easier, even for a non-fabricator[125]. These projects, as well as several others that deal specifically with digital fabrication for laser cutting[65][120], are examples of the subset of tangible interfaces to which this work belongs - namely, those concerned with providing a means to engage with digital fabrication technologies in a more intuitive, embodied fashion. However, with the exception of KidCAD and Easigami these designs are not made with children in mind, nor

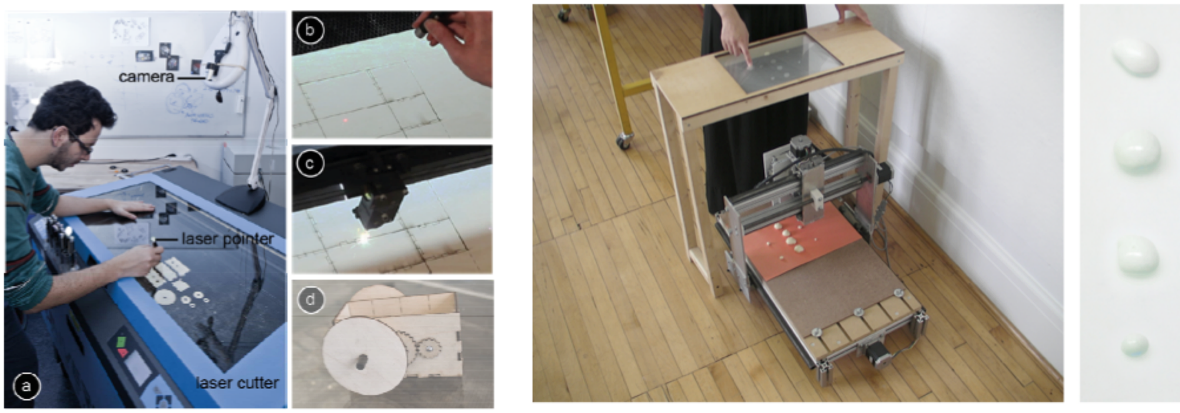


Figure 3.2: Examples of interactive fabrication interfaces: Constructable (left) allows users to control a laser cutter with a set of physical tools as opposed to a pre-defined design file. Shaper (right), and interactive fabrication tool using expanding polyurethane foam.

do they cover the range of possibilities for child-friendly input devices that focus on 3D-printing. Thus we argue that there is room for exploration in this area, as well as a lineage that suggests meaningful results may follow from the incorporation of tangible interfaces with embodied design.

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 Nuez [18]: the authors discuss physically- derived metaphors that underlie such essential mathematical ideas as numbers, operations, and sets. Such notions of embodied mathematics haveeven before the Lakoff/Nuez textplayed 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],

Figure 3.3: Left: The KidCAD interface showing a model Zebra and its 2.5D impression on screen. Right: The Easigami system, showing a series of connected polygonal faces with smart-hinges and embedded electronics.

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 studentsyounger, 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 studentsparticularly if (as we anticipate) the device and software are made more expressive or powerful in future iterations. It should also be noted, along these lines, that our early pilot test experience suggests a potentially fruitful use for the UCube as an assessment device for children's spatial cognition. (The young subject who suggested that it could be made into a "puzzle game" is anticipating our thoughts here!) A researcher could, for instance, give children a pattern of lights and ask them to match that pattern to one of a set of physical or pictorial solid representations; or one might ask children to recreate a variety of physical solids (such as a plastic prism or tetrahedron) by selecting the appropriate set of lights, and note their development and difficulties in doing so. By using the UCube as an experimental 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).

Chapter 4

Technical Implementation

Chapter 5

Evaluation

This section is devoted to the description and discussion of three separate user studies with the devices discussed in Chapter 2. Two studies were performed with the original UCube device (one more informal than the other), while a longer study involved both the SnapCAD and PopCAD systems.

5.1 UCube Pilot

5.1.1 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 as in Figure 5.1. 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

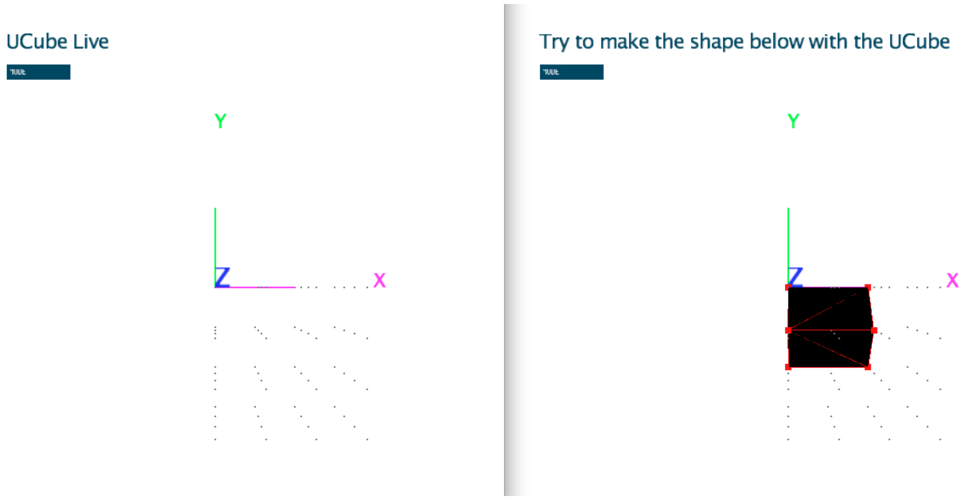


Figure 5.1: A screenshot of the testing setup, with the live output from the UCube on the right and the target shape on the left.

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 toolhow well it could help "3D novices" overcome the "2D bottleneck".

5.1.2 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 XXXX, for exampleshown earlier in the context of explaining the UCube’s operationdepicts 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.

5.2 Further UCube Study

Early in 2012, we conducted a further user study of the UCube with a group of 11-13 year olds. The group consisted of ten participants, eight boys and two girls, from a local middle school multimedia class. Every participant was individually led through two separate exercises (outlined below) using the UCube.

5.2.1 Procedure: Modeling

Participants were handed a 3D-printed shape (modeled and printed from the UCube) and were instructed to attempt to model the shape using the UCube. The participant was initially allowed to hold the shape for approximately 10 seconds, after which they would hand the shape back to the facilitator and attempt to model the shape from memory. Participants were instructed that they may ask to hold the shape again, at which point they were allowed to hold it throughout the duration of the modeling task. Additionally, users were instructed that they had the option to skip a shape and return to it at a later point in the exercise. The five physical shapes presented were: a cube, a tetrahedron, a diamond, a "house" (a cube with a pyramid on top), and a complex irregular polyhedron. The models were presented to the user starting with the cube (as this was deemed to be the most basic shape with regard to modeling complexity). To avoid an ordering bias, we randomized the presentation sequence of the next four shapes using an online random order generator. If, after skipping a shape and returning to it, the participant was still having difficulty, we offered them the opportunity to attempt modeling the shape with the help of the UCube software, the effects of which are discussed in the results section. Participants were given a total of 25 minutes for the modeling exercise. We recorded, but did not limit the modeling time per shape, only the total time for all five shapes.

5.2.2 Procedure: Matching

Participants were instructed to face away from the UCube while the facilitator modeled a set of lights on the UCube corresponding to one shape among a set of physical models laid out on the table next to the UCube. Once the lights on the UCube were set up, the participant was instructed to turn around, and indicate which physical object they thought the set of lights on the UCube corresponded to. There were nine physical models presented on the table, and consisted of a cube, a tetrahedron, the house shape, a diamond, a triangular prism, an elongated hexagon, a parallelogram, a trapezoid, and an irregular polyhedron (see Figure 5.2 for a picture of all the models). The shapes were always presented on the table in the same order and orientation to avoid discrepancies in perception or association. Of the nine shapes, the participants were asked to match five of them (the cube, the triangular prism, the parallelogram, the elongated hexagon, and the trapezoid). Thus, only the cube was presented in both the matching and modeling exercises. As with the modeling exercise, the cube was presented first, with the remaining four shapes presented in a computer-generated randomized order.Participants were given a total of ten minutes for the matching exercise, corresponding to two minutes per shape, and were instructed to think aloud during the process.

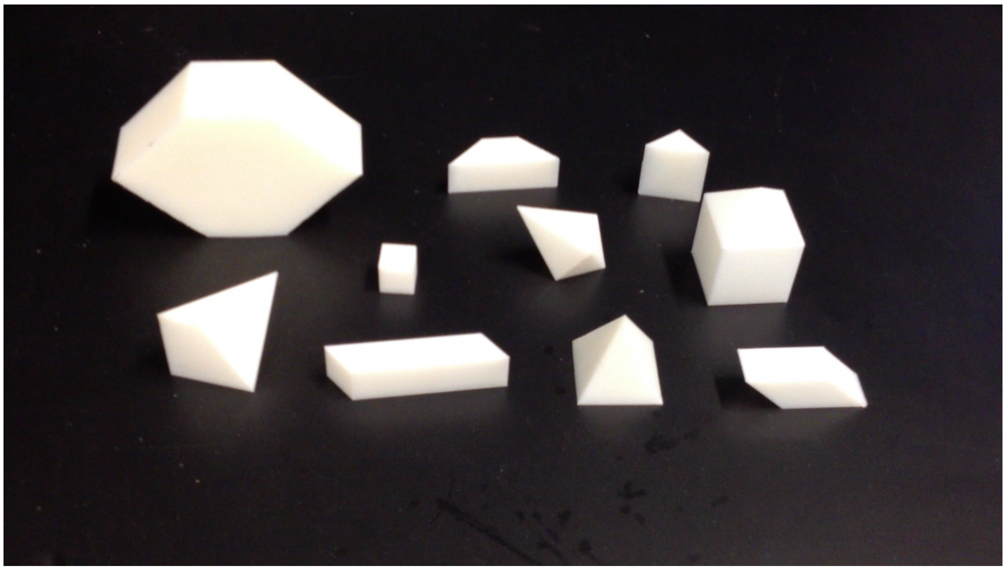


Figure 5.2: The nine 3D-printed models used in the modeling and matching tasks described in this section.

5.2.3 Results

While many established forms of 3D modeling systems can be confounding and operationally too complex for a child to navigate, the UCube was positively received and system instruction was accomplished with just a minor introduction and demonstration (system instruction and demonstration lasted approximately 2-3 minutes). We found this first instance of system comprehension to offer some validation that the UCube worked well as a user-friendly 3D modeling device. This section will detail the outcome of both the modeling and matching tasks performed.

5.2.3.1 Exercise 1: Modeling

Modeling occurred under three conditions:recreate the object from memory, construction of the object while it was in the participants possession, and modeling the shape with the help of the

UCube software. Overall, 21 of 50 shapes were completed from memory, 12 of 50 were completed while holding the shape, and a further 8 of 50 were completed with the aid of the UCube software, for a total of 41 out of 50 shapes modeled successfully (82%). Of the nine missed shapes, seven were of the same shape, the complex polyhedron. The remaining two misses were from the same participant, who ran out of time before completion. Of the 10 participants, 8 were able to recreate the cube from memory, whereas only 4 were able to recreate the diamond and the tetrahedron from memory. Half of the participants constructed the house from memory, and no participants were able to complete the irregular polyhedron from memory. However, once shown the software the majority of the participants found the modeling task significantly easier to perform. The irregular polyhedron was by far the hardest shape and was only able to be completed by 3 of the 10 participants either after continued possession of the shape or using the software.

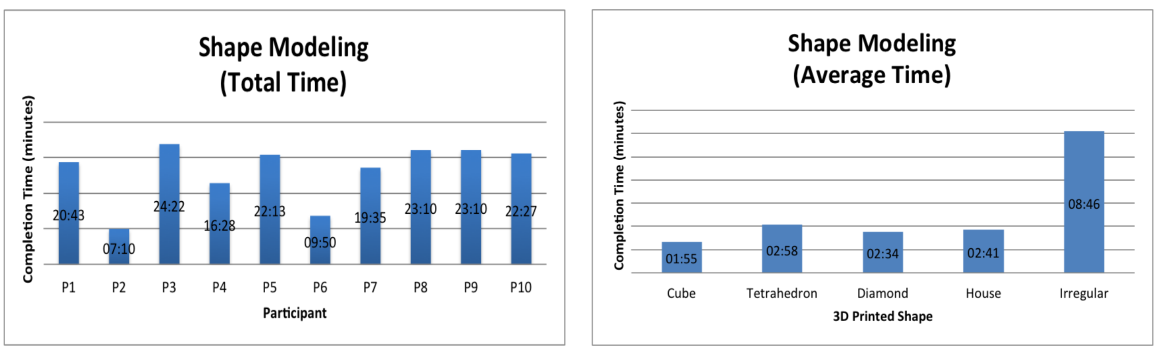
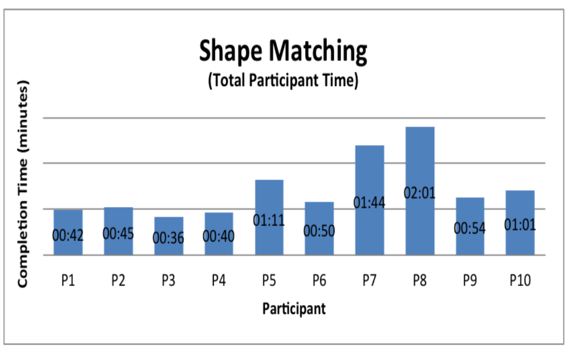


Figure 5.3: Results of the modeling task, showing total modeling time spent per participant (left) and average modeling time spent per shape across participants (right).

Figure 5.3 represents the total completion times per participant (on the left) and average time per shape (right). Two exceptional completion times were observed, where participants finished modeling all the shapes in under 10 minutes. However, the majority of participants finished the task in the 19-25 minute range. Only one of the participants ran out of time. Once participants had been introduced to the software, 9 of 10 of participants were able to complete all but the irregular polyhedron. It is interesting to note that of the 10 participants, the child that had the most difficult time modeling, the lowest shape completion rate, and the longest completion time during the matching exercise was the youngest participant.

5.2.3.2 Exercise 2: Matching

Out of 50 matching tasks (five per participant), all but three tasks were completed in 20 seconds or less. Figure 5.4 displays the total time spent on the matching task per participant (left) and the average completion times for each shape (right). No participant selected the wrong shape (a few preliminary "mis-selections" were made that the participants quickly corrected), and all participants completed the task in well under the allotted 10 minutes. The lack of errors in the matching task is highly encouraging as a basis from which to reason about youngsters' abilities to perceive and reason about convex hulls as a set of lit vertices in space, meaning that this kind of 3D modeling interface might be applied to other domains (e.g., as a cognitive assessment tool, a puzzle game, etc.) with some optimism.



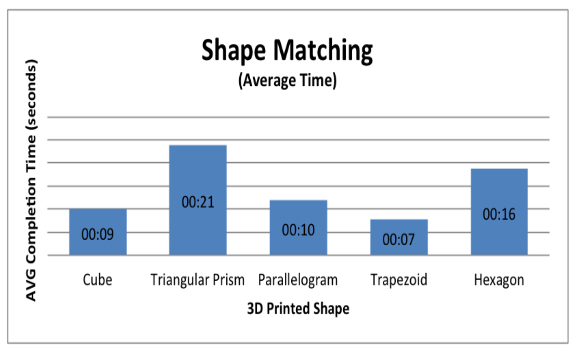


Figure 5.4: Results of the matching task, showing total time spent per participant (left) and average time spent per shape across participants (right).

5.2.3.3 Observations

Modeling trends as well as distinct modeling behaviors were documented in the process. Common observations included building from the ground up (lowest vertices first), building in the orientation that the object had been presented in, not clearing the poles/lights from the UCube before starting to model a new shape, and modeling a shape by breaking it up into discrete parts (e.g. a participant building a house would commonly build a cube first and then add on a vertex to the top; a participant constructing the diamond might combine two opposite facing triangles.).

Unique behaviors were exhibited in the modeling process as well, reflecting a type of user-specific construction-based problem- solving. One participant used their arm to connect the red lights of the UCube for shape definition. A few participants oriented the object differently than how it had been presentedtypically this occurred for the modeling of those objects with a pyramidal apex (tetrahedron, house, diamond). Apex formation was perhaps one of the most difficult concepts for most participants to grasp, as it required them to strategically align the base on a 3x3 grid so there was a middle plug for them to create the apex. If participants were fixated on designing from a 4x4 grid then there was no center plug for them to create a midpoint. Some participants ended up building an oblong polyhedron as opposed to a cube, or an oblique polyhedron as opposed to an equilateral tetrahedron. Other observed behaviors included a participant who modeled shapes by turning on lights for an entire shape edge, as opposed to just the corners and a participant who built shapes that were floating, as opposed to resting on the base of the UCube. There were also some notable behaviors regarding physical and gestural actions of the participants. Many participants modeled with both hands simultaneously, placing towers and flipping switches without a clear preference for a dominant hand. Participants would often gesture with their arms following an arc in parallel with a face of the object they were currently modeling. This tracing behavior was also noticed when participants were holding a physical model and tracing a side of the object with their fingertip, often while rotating the object with the other hand. Finally, during object possession phase three participants actually placed the 3D object on top of the UCube in the modeling space while they reasoned out the construction (see Figure 5.5 for an example).

5.3 SnapCAD and PopCAD

The study will comprise several stages, the first being a pre-assessment of spatial reasoning skills (all spatial reasoning assessment will be done using the 'Children's Mental Transformation Task' designed by Susan Levine - see http://silccenter.org/index.php/testsainstrumentsMRT for the

instruments, see http://www.spatialintelligence.org/publications$_{p}dfs/Ehrlich\%20Levine\%20\%20Goldin-$
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After the consent and assent forms are completed and the study session starts, participants will be seated and will go through an explanation of the entire study and what they will be asked to do. The pre-assessment will then be given, consisting of 10 brief exercises where the participant attempts to match a spatially transformed shape, printed on paper along with several incorrect choices, to its original counterpart.

Participants will then be seated in front of a desk on which either the PopCAD interface (a pop-up book) or SnapCAD (a tower and magnetic light based interface) has been placed. The device will be hooked up to a laptop on the desk. Participants will be given a brief demo of how to interact with the device and how the software responds to those interactions.

The tasks that follow are the same for each device:

Task 1: Convex Hull Modeling

The participant will be given a brief demo of how the convex hull modeling mode interprets the points from the device. The user will then be presented with a series of four (4) plastic, 3D-printed models that were modeled on the device using convex hull mode. The 4 shapes will be presented in a computer-generated random order. For each of these shapes, the participant will attempt to recreate the shape using the modeling abilities of the device. The user will be instructed to indicate when they believe they are done, as well as to think aloud about their modeling process. Each modeling task will be capped at 10 minutes. The time to completion (of lack thereof), observational notes, and video shall be recorded.

Task 2: Path Modeling

The participant will be given a brief demo of how the path modeling mode interprets the points from the device. The user will then be presented with a series of four (4) plastic, 3D-printed models that were modeled on the device using the path mode. The 4 shapes will be presented in a computer-generated random order. For each of these shapes, the participant will attempt to recreate the shape using the modeling abilities of the device. The user will be instructed to indicate when they believe they are done, as well as to think aloud about their modeling process. Each modeling task will be capped at 10 minutes. The time to completion (of lack thereof), observational notes, and video shall be recorded.

Task 3: Minimal Spanning Tree Modeling

The participant will be given a brief demo of how the minimal spanning tree (aka tree) modeling mode interprets the points from the device. The user will then be presented with a series of four (4) plastic, 3D-printed models that were modeled on the device using the tree mode. The 4 shapes will be presented in a computer-generated random order. For each of these shapes, the participant will attempt to recreate the shape using the modeling abilities of the device. The user will be instructed to indicate when they believe they are done, as well as to think aloud about their modeling process. Each modeling task will be capped at 10 minutes. The time to completion (of lack thereof), observational notes, and video shall be recorded.

Task 4: Freehand Modeling

The freehand activity will occur before and after the modeling tasks and will serve to get a sense of the overall usability of the interface as well as a sense of the expressive range of each device. By asking participants to think aloud about their intentions and thinking processes, a deeper understanding may be gained of the strengths and weaknesses of the system. Additionally, the modeling modes used, relative time spent using each mode, and complexity (in number of points) of the objects modeled will be recorded.

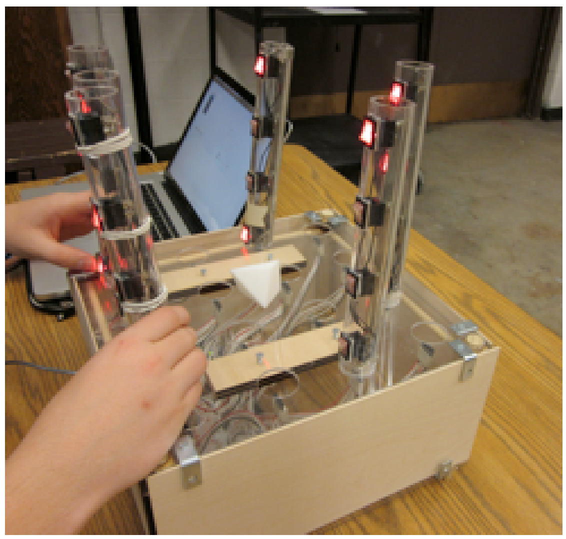

Figure 5.5: A participant modeling with the UCube, using a strategy of placing the physical model on top of the UCube while modeling, as well as using both hands simultaneously to manipulate the towers.

Chapter 6

Vision

Chapter 7

Future Work

Bibliography

[1] The printed world. http://www.economist.com/node/18114221, 2011.

[2] 123d catch. http://www.123dapp.com/catch, 2013.

[3] Makerbot. http://www.makerbot.com/, 2013.

[4] Ponoko. http://www.ponoko.com/, 2013.

[5] Stratasys. http://www.stratasys.com/, 2013.

[6] Thingiverse. http://www.thingiverse.com/, 2013.

[7] Tinkercad. http://www.tinkercad.com/, 2013.

[8] Dor Abrahamson and Dragan Trninic. Toward an embodied-interaction design framework for mathematical concepts. In Proceedings of the 10th International Conference on Interaction Design and Children, IDC '11, pages 1–10, New York, NY, USA, 2011. ACM.

[9] S. Ananthanarayan, K. Siek, and M. Eisenberg. Towards the Crafting of Personal Health Technologies. Submitted for publication. 2013.

[10] C. Anderson. Makers: The New Industrial Revolution. Random House, 2012.

[11] Alissa N. Antle. Designing tangibles for children: what designers need to know. In CHI '07 Extended Abstracts on Human Factors in Computing Systems, CHI EA '07, pages 2243–2248, New York, NY, USA, 2007. ACM.

[12] Alissa N. Antle, Milena Droumeva, and Daniel Ha. Thinking with hands: an embodied approach to the analysis of children's interaction with computational objects. In CHI '09 Extended Abstracts on Human Factors in Computing Systems, CHI EA '09, pages 4027–4032, New York, NY, USA, 2009. ACM.

[13] Alissa N. Antle and Sijie Wang. Comparing motor-cognitive strategies for spatial problem solving with tangible and multi-touch interfaces. In Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction, TEI '13, pages 65–72, New York, NY, USA, 2013. ACM.

[14] Alissa N. Antle, Alyssa F. Wise, and Kristine Nielsen. Towards utopia: designing tangibles for learning. In Proceedings of the 10th International Conference on Interaction Design and Children, IDC '11, pages 11–20, New York, NY, USA, 2011. ACM.

[15] Saskia Bakker, Alissa N Antle, and Elise Van Den Hoven. Embodied metaphors in tangible interaction design. Personal and Ubiquitous Computing, 16(4):433–449, 2012.

[16] Saskia Bakker, Elise van den Hoven, and Alissa N Antle. Moso tangibles: evaluating embodied learning. In Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction, pages 85–92. ACM, 2011.

[17] Nicholas A Basbanes. On Paper: The Everything of Its Two-Thousand-Year History. Random House LLC, 2013.

[18] RQRQ Berry, G Bull, C Browning, C Thomas, K Starkweather, and J Aylor. Preliminary considerations regarding use of digital fabrication to incorporate engineering design principles in elementary mathematics education. Contemporary Issues in Technology and Teacher Education, 10(2):167–172, 2010.

[19] Allen Bevans, Ying-Ting Hsiao, and Alissa Antle. Supporting children's creativity through tangible user interfaces. In CHI '11 Extended Abstracts on Human Factors in Computing Systems, CHI EA '11, pages 1741–1746, New York, NY, USA, 2011. ACM.

[20] Jack Breen, Robert Nottrot, and Martijn Stellingwerff. Tangible virtualityperceptions of computer-aided and physical modelling. Automation in Construction, 12(6):649–653, 2003.

[21] Erwin H Brinkmann. Programed instruction as a technique for improving spatial visualization. Journal of Applied Psychology, 50(2):179, 1966.

[22] Norman Brosterman, Kiyoshi Togashi, and Eric Himmel. Inventing kindergarten. HN Abrams New York, NY, 1997.

[23] Craig Brown and Amy Hurst. Viztouch: automatically generated tactile visualizations of coordinate spaces. In Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction, TEI '12, pages 131–138, New York, NY, USA, 2012. ACM.

[24] Leah Buechley and Michael Eisenberg. The lilypad arduino: Toward wearable engineering for everyone. Pervasive Computing, IEEE, 7(2):12–15, 2008.

[25] Leah Buechley, Mike Eisenberg, Jaime Catchen, and Ali Crockett. The lilypad arduino: using computational textiles to investigate engagement, aesthetics, and diversity in computer science education. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, CHI '08, pages 423–432, New York, NY, USA, 2008. ACM.

[26] Leah Buechley, Sue Hendrix, and Mike Eisenberg. Paints, paper, and programs: first steps toward the computational sketchbook. In Proceedings of the 3rd International Conference on Tangible and Embedded Interaction, pages 9–12. ACM, 2009.

[27] Leah Buechley, David Mellis, Hannah Perner-Wilson, Emily Lovell, and Bonifaz Kaufmann. Living wall. In Proceedings of the international conference on Multimedia - MM '10, page 1401, New York, New York, USA, October 2010. ACM Press.

[28] Leah Buechley and Hannah Perner-Wilson. Crafting technology. ACM Transactions on Computer-Human Interaction, 19(3):1–21, October 2012.

[29] A. Clark. Being There: Putting Brain, Body, and World Together Again. A Bradford book. MIT Press, 1998.

[30] Marcelo Coelho, L Hall, J Berzowska, and P Maes. Pulp-based computing: a framework for building computers out of paper. ...Human Factors in Computing ..., pages 3527–3528, 2009.

[31] Matthew Conway, Steve Audia, Tommy Burnette, Dennis Cosgrove, and Kevin Christiansen. Alice: lessons learned from building a 3d system for novices. In Proceedings of the SIGCHI conference on Human Factors in Computing Systems, CHI '00, pages 486–493, New York, NY, USA, 2000. ACM.

[32] Stacy B Ehrlich, Susan C Levine, and Susan Goldin-Meadow. The importance of gesture in children's spatial reasoning. Developmental psychology, 42(6):1259, 2006.

[33] M. Eisenberg, A. Eisenberg, S. Hendrix, G. Blauvelt, D. Butter, J. Garcia, R. Lewis, and T. Nielsen. As we may print: new directions in output devices and computational crafts for children. In Proceedings of the 2003 conference on Interaction design and children, IDC '03, pages 31–39, New York, NY, USA, 2003. ACM.

[34] Michael Eisenberg. Pervasive fabrication: Making construction ubiquitous in education. In Proceedings of the Fifth IEEE International Conference on Pervasive Computing and Communications Workshops, PERCOMW '07, pages 193–198, Washington, DC, USA, 2007. IEEE Computer Society.

[35] Michael Eisenberg. Educational fabrication, in and out of the classroom. In Society for Information Technology & Teacher Education International Conference, volume 2011, pages 884–891, 2011.

[36] Michael Eisenberg, Nwanua Elumeze, Michael MacFerrin, and Leah Buechley. Children's programming, reconsidered: settings, stuff, and surfaces. In Proceedings of the 8th International Conference on Interaction Design and Children, IDC '09, pages 1–8, New York, NY, USA, 2009. ACM.

[37] Michael Eisenberg, Wendy Mackay, Allison Druin, Sheila Lehman, and Mitchel Resnick. Real meets virtual: blending real-world artifacts with computational media. In Conference Companion on Human Factors in Computing Systems, CHI '96, pages 159–160, New York, NY, USA, 1996. ACM.

[38] Michael Eisenberg, Ann Nishioka, and M. E. Schreiner. Helping users think in three dimensions: steps toward incorporating spatial cognition in user modelling. In Proceedings of the 2nd international conference on Intelligent user interfaces, IUI '97, pages 113–120, New York, NY, USA, 1997. ACM.

[39] Fab@Home. www.fabathome.org. 2011.

[40] Desktop Factory. www.desktopfactory.com/. 2011.

[41] ES Ferguson. Engineering and the Mind's Eye. The MIT Press, 1992.

[42] Thomas Fischer and Wing Lau. Marble track music sequencers for children. In Proceedings of the 2006 conference on Interaction design and children, IDC '06, pages 141–144, New York, NY, USA, 2006. ACM.

[43] Sean Follmer and Hiroshi Ishii. Kidcad: digitally remixing toys through tangible tools. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, CHI '12, pages 2401–2410, New York, NY, USA, 2012. ACM.

[44] Sean Follmer, Micah Johnson, Edward Adelson, and Hiroshi Ishii. deform: an interactive malleable surface for capturing 2.5d arbitrary objects, tools and touch. In Proceedings of the 24th annual ACM symposium on User interface software and technology, UIST '11, pages 527–536, New York, NY, USA, 2011. ACM.

[45] F. Froebel and J. Jarvis. The Education of Man. A. Lovell Company, New York, 1886.

[46] Neil Gershenfeld. Fab: The Coming Revolution on Your Desktop–from Personal Computers to Personal Fabrication. Basic Books, Inc., New York, NY, USA, 2007.

[47] Wooi Boon Goh, L. L. Chamara Kasun, Fitriani, Jacquelyn Tan, and Wei Shou. The i-cube: design considerations for block-based digital manipulatives and their applications. In Proceedings of the Designing Interactive Systems Conference, DIS '12, pages 398–407, New York, NY, USA, 2012. ACM.

[48] H. Nusbaum S. D. Delly Goldin-Meadow, S. and S. Wagner. Explaining math: Gesturing lightens the load. Psychological Science, pages pp. 516–22, 1991.

[49] Ira Greenberg. Processing: creative coding and computational art. Apress, 2007.

[50] Mark D. Gross and Michael Eisenberg. Why toys shouldn't work "like magic": Children's technology and the values of construction and control. In Proceedings of the The First IEEE International Workshop on Digital Game and Intelligent Toy Enhanced Learning, DIGITEL '07, pages 25–32, Washington, DC, USA, 2007. IEEE Computer Society.

[51] Elizabeth G Hainstock. The Essential Montessori. New American Library, 1978.

[52] B. Hart. Will 3d printing change the world? http://www.forbes.com/sites/gcaptain/2012/03/06/will-3d-prin 2012.

[53] George W Hart. Procedural generation of sculptural forms. Bridges, 2008:209, 2008.

[54] Susan Lee Hendrix. Popup Workshop: Computationally Enhanced Paper Engineering for Children. PhD thesis, University of Colorado, 2008.

[55] Mark Howison, Dragan Trninic, Daniel Reinholz, and Dor Abrahamson. The mathematical imagery trainer: from embodied interaction to conceptual learning. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pages 1989–1998. ACM, 2011.

[56] http://507movements.com/. 507 mechanical movements. 2013.

[57] Yingdan Huang and Michael Eisenberg. Easigami: virtual creation by physical folding. In Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction, TEI '12, pages 41–48, New York, NY, USA, 2012. ACM.

[58] Yingdan Huang, Mark D Gross, Ellen Yi-Luen Do, and Mike Eisenberg. Easigami: a reconfigurable folded-sheet tui. In Proceedings of the 3rd International Conference on Tangible and Embedded Interaction, TEI '09, pages 107–112, New York, NY, USA, 2009. ACM.

[59] Amy Hurst and Shaun Kane. Making "making" accessible. In Proceedings of the 12th International Conference on Interaction Design and Children, IDC '13, pages 635–638, New York, NY, USA, 2013. ACM.

[60] Barbel Inhelder and Jean Piaget. The Growth of Logical Thinking from Childhood to Adolescence : An Essay on the Construction of Formal Operational Structures. Basic, 1958.

[61] Instructables. http://instructables.com.

[62] Hiroshi Ishii. Tangible bits: beyond pixels. In Proceedings of the 2nd international conference on Tangible and embedded interaction, TEI '08, pages xv–xxv, New York, NY, USA, 2008. ACM.

[63] Hiroshi Ishii and Brygg Ullmer. Tangible bits: towards seamless interfaces between people, bits and atoms. In Proceedings of the ACM SIGCHI Conference on Human factors in computing systems, CHI '97, pages 234–241, New York, NY, USA, 1997. ACM.

[64] Sam Jacoby and Leah Buechley. Drawing the electric. In Proceedings of the 12th International Conference on Interaction Design and Children - IDC '13, pages 265–268, New York, New York, USA, June 2013. ACM Press.

[65] Gabe Johnson, Mark Gross, Ellen Yi-Luen Do, and Jason Hong. Sketch it, make it: sketching precise drawings for laser cutting. In CHI '12 Extended Abstracts on Human Factors in Computing Systems, CHI EA '12, pages 1079–1082, New York, NY, USA, 2012. ACM.

[66] Samuel Johnson and AnnMarie P. Thomas. Squishy circuits: a tangible medium for electronics education. In CHI '10 Extended Abstracts on Human Factors in Computing Systems, CHI EA '10, pages 4099–4104, New York, NY, USA, 2010. ACM.

[67] Yasmin B. Kafai, Kylie A. Peppler, Quinn Burke, Michael Moore, and Diane Glosson. Frbel's forgotten gift: textile construction kits as pathways into play, design and computation. In Proceedings of the 9th International Conference on Interaction Design and Children, IDC '10, pages 214–217, New York, NY, USA, 2010. ACM.

[68] Yoshihiro Kawahara, Steve Hodges, Benjamin S Cook, and Gregory D Abowd. Instant Inkjet Circuits : Lab-based Inkjet Printing to Support Rapid Prototyping of UbiComp Devices. pages 363–372, 2013.

[69] Yoshihiro Kawahara, Steve Hodges, Benjamin S. Cook, Cheng Zhang, and Gregory D. Abowd. Instant inkjet circuits. In Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing - UbiComp '13, page 363, New York, New York, USA, September 2013. ACM Press.

[70] Scott R. Klemmer, Björn Hartmann, and Leila Takayama. How bodies matter: five themes for interaction design. In Proceedings of the 6th conference on Designing Interactive systems, DIS '06, pages 140–149, New York, NY, USA, 2006. ACM.

[71] Naoya Koizumi, Kentaro Yasu, Angela Liu, Maki Sugimoto, and Masahiko Inami. Animated paper. Computers in Entertainment, 8(2):1, December 2010.

[72] Dennis Krannich, Bernard Robben, and Sabrina Wilske. Digital fabrication for educational contexts. In Proceedings of the 11th International Conference on Interaction Design and Children, IDC '12, pages 375–376, New York, NY, USA, 2012. ACM.

[73] G. Lakoff and R. Nuñez. Where Mathematics Come From: How The Embodied Mind Brings Mathematics Into Being. Basic Books, Inc., 2001.

[74] Ben Leduc-Mills and Michael Eisenberg. The ucube: a child-friendly device for introductory three-dimensional design. In Proceedings of the 10th International Conference on Interaction Design and Children, IDC '11, pages 72–80, New York, NY, USA, 2011. ACM.

[75] Ben Leduc-Mills, Halley Profita, and Michael Eisenberg. "seeing solids" via patterns of light: evaluating a tangible 3d-input device. In Proceedings of the 11th International Conference on Interaction Design and Children, IDC '12, pages 377–380, New York, NY, USA, 2012. ACM.

[76] Hod Lipson and Melba Kurman. Factory@ home: The emerging economy of personal fabrication. A report commissioned by the US Office of Science and Technology Policy, 2010.

[77] Hod Lipson, Francis C Moon, Jimmy Hai, and Carlo Paventi. 3-d printing the history of mechanisms. Journal of Mechanical Design, 127:1029, 2005.

[78] Evan Malone and Hod Lipson. Fab@ home: the personal desktop fabricator kit. Rapid Prototyping Journal, 13(4):245–255, 2007.

[79] James H Mathewson. Visual-spatial thinking: An aspect of science overlooked by educators. Science Education, 83(1):33–54, 1999.

[80] Timothy S. McNerney. From turtles to tangible programming bricks: explorations in physical language design. Personal Ubiquitous Comput., 8(5):326–337, September 2004.

[81] Arduino Mega. arduino.cc/en/main/arduinoboardmega2560. 2011.

[82] David A. Mellis, Sam Jacoby, Leah Buechley, Hannah Perner-Wilson, and Jie Qi. Microcontrollers as material: crafting circuits with paper, conductive ink, electronic components, and an "untoolkit". In Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction, TEI '13, pages 83–90, New York, NY, USA, 2013. ACM.

[83] Jason Mickelson and Wendy Ju. Math propulsion: engaging math learners through embodied performance & visualization. In Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction, pages 101–108. ACM, 2011.

[84] Maria Montessori. The Montessori Method. Frederick Stokes Co., New York, NY, 1912.

[85] Catarina Mota. The rise of personal fabrication. In Proceedings of the 8th ACM conference on Creativity and cognition, pages 279–288. ACM, 2011.

[86] Stefanie Mueller, Bastian Kruck, and Patrick Baudisch. LaserOrigami. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '13, page 2585, New York, New York, USA, April 2013. ACM Press.

[87] Stefanie Mueller, Pedro Lopes, and Patrick Baudisch. Interactive construction: interactive fabrication of functional mechanical devices. In Proceedings of the 25th annual ACM symposium on User interface software and technology, UIST '12, pages 599–606, New York, NY, USA, 2012. ACM.

[88] Ricardo Nemirovsky, Cornelia Tierney, and Tracey Wright. Body motion and graphing. Cognition and instruction, 16(2):119–172, 1998.

[89] Nora Newcombe and Janellen Huttenlocher. Making space: The development of spatial representation and reasoning. The MIT Press, 2003.

[90] Brian N. O'Connell. The development of the paperbots robotics kit for inexpensive robotics education activities for elementary students. Master's thesis, Tufts University, 2013.

[91] S. Papert. Mindstorms: Children, Computers, and Powerful Ideas. Basic Books, Inc., 1980.

[92] Amanda J. Parkes, Hayes Solos Raffle, and Hiroshi Ishii. Topobo in the wild: longitudinal evaluations of educators appropriating a tangible interface. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, CHI '08, pages 1129–1138, New York, NY, USA, 2008. ACM.

[93] Jean Piaget and Barbel Inhelder. The childs conception of space (fj langdon & jl lunzer, trans.). New York, 1967.

[94] Processing. www.processing.org. 2011.

[95] The RepRap Project. reprap.org/wiki/main$_{page.}$2011.

[96] Jie Qi and Leah Buechley. Electronic popables: exploring paper-based computing through an interactive pop-up book. In Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction, TEI '10, pages 121–128, New York, NY, USA, 2010. ACM.

[97] Jie Qi and Leah Buechley. Animating paper using shape memory alloys. In Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI '12, page 749, New York, New York, USA, May 2012. ACM Press.

[98] Hayes Solos Raffle. Sculpting behavior: a tangible language for hands-on play and learning. PhD thesis, MIT, Cambridge, MA, USA, 2008. AAI0821001.

[99] Hayes Solos Raffle, Amanda J. Parkes, and Hiroshi Ishii. Topobo: a constructive assembly system with kinetic memory. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, CHI '04, pages 647–654, New York, NY, USA, 2004. ACM.

[100] Betty Repacholi and Alison Gopnik. Early reasoning about desires: Evidence from 14- and 18-month-olds. In Developmental Psychology, pages 12–21, 1997.

[101] Mitchel Resnick. All i really need to know (about creative thinking) i learned (by studying how children learn) in kindergarten. In Proceedings of the 6th ACM SIGCHI conference on Creativity & cognition, C&C '07, pages 1–6, New York, NY, USA, 2007. ACM.

[102] Mitchel Resnick, Fred Martin, Robert Berg, Rick Borovoy, Vanessa Colella, Kwin Kramer, and Brian Silverman. Digital manipulatives: new toys to think with. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, CHI '98, pages 281–287, New York, NY, USA, 1998. ACM Press/Addison-Wesley Publishing Co.

[103] Mitchel Resnick and Brian Silverman. Some reflections on designing construction kits for kids. In Proceedings of the 2005 conference on Interaction design and children, IDC '05, pages 117–122, New York, NY, USA, 2005. ACM.

[104] Rhino. www.rhino3d.com. 2011.

[105] Eric Rosenbaum and Jay Silver. Makey makey: improvising tangible and nature-based user interfaces. In Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction, TEI '12, pages 367–370, New York, NY, USA, 2012. ACM.

[106] Greg Saul, Cheng Xu, and Mark D. Gross. Interactive paper devices. In Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction - TEI '10, page 205, New York, New York, USA, January 2010. ACM Press.

[107] Eric Schweikardt, Nwanua Elumeze, Mike Eisenberg, and Mark D Gross. A tangible construction kit for exploring graph theory. In Proceedings of the 3rd International Conference on Tangible and Embedded Interaction, TEI '09, pages 373–376, New York, NY, USA, 2009. ACM.

[108] Eric Schweikardt and Mark D. Gross. roblocks: a robotic construction kit for mathematics and science education. In Proceedings of the 8th international conference on Multimodal interfaces, ICMI '06, pages 72–75, New York, NY, USA, 2006. ACM.

[109] Shapeways. www.shapeways.com. 2011.

[110] Francis T Siemankowski and Franklin C MacKnight. Spatial cognition, a success prognosticator in college science courses. 1971.

[111] Arnan Sipitakiat and Nusarin Nusen. Robo-blocks: designing debugging abilities in a tangible programming system for early primary school children. In Proceedings of the 11th International Conference on Interaction Design and Children, IDC '12, pages 98–105, New York, NY, USA, 2012. ACM.

[112] Google SketchUp. sketchup.google.com/. 2011.

[113] Solidways. www.solidworks.com. 2011.

[114] J. P. Spencer, M. Clearfield, D. Corbetta, B. Ulrich, P. Buchanan, and G. Schoner. Moving toward a grand theory of development: In memory of esther thelen. In Child Development, pages 1521–1538, 2006.

[115] Cristina Sylla, Pedro Branco, Sérgio Gonçalves, Clara Coutinho, and Paulo Brito. t-books. In Proceedings of the 11th International Conference on Interaction Design and Children - IDC '12, page 323, New York, New York, USA, June 2012. ACM Press.

[116] Danli Wang, Cheng Zhang, and Hongan Wang. T-maze: a tangible programming tool for children. In Proceedings of the 10th International Conference on Interaction Design and Children, IDC '11, pages 127–135, New York, NY, USA, 2011. ACM.

[117] Ryoichi Watanabe, Yuichi Itoh, Masatsugu Asai, Yoshifumi Kitamura, Fumio Kishino, and Hideo Kikuchi. The soul of activecube: implementing a flexible, multimodal, three-dimensional spatial tangible interface. Comput. Entertain., 2(4):15–15, October 2004.

[118] Michael Philetus Weller, Ellen Yi-Luen Do, and Mark D Gross. Escape machine: teaching computational thinking with a tangible state machine game. In Proceedings of the 7th international conference on Interaction design and children, IDC '08, pages 282–289, New York, NY, USA, 2008. ACM.

[119] Michael Philetus Weller, Mark D. Gross, and Ellen Yi-Luen Do. Tangible sketching in 3d with posey. In CHI '09 Extended Abstracts on Human Factors in Computing Systems, CHI EA '09, pages 3193–3198, New York, NY, USA, 2009. ACM.

[120] Karl D.D. Willis, Juncong Lin, Jun Mitani, and Takeo Igarashi. Spatial sketch: bridging between movement & fabrication. In Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction, TEI '10, pages 5–12, New York, NY, USA, 2010. ACM.

[121] Karl D.D. Willis, Cheng Xu, Kuan-Ju Wu, Golan Levin, and Mark D. Gross. Interactive fabrication: new interfaces for digital fabrication. In Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction, TEI '11, pages 69–72, New York, NY, USA, 2011. ACM.

[122] Margaret Wilson. Six views of embodied cognition. Psychonomic Bulletin Review, 9(4):625–636, 2002.

[123] Lesley Xie, Alissa N. Antle, and Nima Motamedi. Are tangibles more fun?: comparing children's enjoyment and engagement using physical, graphical and tangible user interfaces. In Proceedings of the 2nd international conference on Tangible and embedded interaction, TEI '08, pages 191–198, New York, NY, USA, 2008. ACM.

[124] Kening Zhu, Hideaki Nii, Owen Noel Newton Fernando, and Adrian David Cheok. Selective inductive powering system for paper computing. In Proceedings of the 8th International Conference on Advances in Computer Entertainment Technology - ACE '11, page 1, New York, New York, USA, November 2011. ACM Press.

[125] Amit Zoran and Joseph A. Paradiso. Freed: a freehand digital sculpting tool. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, CHI '13, pages 2613–2616, New York, NY, USA, 2013. ACM.

[126] Oren Zuckerman, Saeed Arida, and Mitchel Resnick. Extending tangible interfaces for education: digital montessori-inspired manipulatives. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, CHI '05, pages 859–868, New York, NY, USA, 2005. ACM.

Appendix A

Weird Exam Answers

About appendices: Each appendix follow the same page-numbering rules as a regular chapter; the first page of a (multi-page) appendix is not numbered. By the way, the following are supposedly authentic answers to English GCSE exams!

(1) The Greeks were a highly sculptured people, and without them we wouldn't have history. The Greeks also had myths. A myth is a female moth.

(2) Actually, Homer was not written by Homer but by another man of that name.

(3) Socrates was a famous Greek teacher who went around giving people advice. They killed him. Socrates died from an overdose of wedlock. After his death, his career suffered a dramatic decline.

(4) Julius Caesar extinguished himself on the battlefields of Gaul. The Ides of March murdered him because they thought he was going to be made king. Dying, he gasped out: Tee hee, Brutus.

(5) Nero was a cruel tyranny who would torture his subjects by playing the fiddle to them.

(6) In midevil times most people were alliterate. The greatest writer of the futile ages was Chaucer, who wrote many poems and verses and also wrote literature.

(7) Another story was William Tell, who shot an arrow through an apple while standing on his sons head.

(8) Writing at the same time as Shakespeare was Miguel Cervantes. He wrote Donkey Hote. The next great author was John Milton. Milton wrote Paradise Lost. Then his wife died and he wrote Paradise Regained.

(9) During the Renaissance America began. Christopher Columbus was a great navigator who discovered America while cursing about the Atlantic. His ships were called the Nina, the Pinta, and the Santa Fe.

(10) Gravity was invented by Issac Walton. It is chiefly noticeable in the autumn when the apples are falling off the trees.

(11) Johann Bach wrote a great many musical compositions and had a large number of children. In between he practiced on an old spinster which he kept up in his attic. Bach died from 1750 to the present. Bach was the most famous composer in the world and so was Handel. Handel was half German half Italian and half English. He was very large.

(12) Soon the Constitution of the United States was adopted to secure domestic hostility. Under the constitution the people enjoyed the right to keep bare arms.

(13) The sun never set on the British Empire because the British Empire is In the East and the sun sets in the West.

(14) Louis Pasteur discovered a cure for rabbis. Charles Darwin was a naturalist who wrote the Organ of the Species. Madman Curie discovered radio. And Karl Marx became one of the Marx brothers.

Appendix B

Ode to Spot

(Data, Stardate 1403827) (A one-page chapter — page must be numbered!) Throughout the ages, from Keats to Giorchamo, poets have composed "odes" to individuals who have had a profound effect upon their lives. In keeping with that tradition I have written my next poem . . . in honor of my cat. I call it. . . Ode. . . to Spot. (Shot of Geordi and Worf in audience, looking mystified at each other.)

> Felus cattus, is your taxonomic nomenclature
> an endothermic quadruped, carnivorous by nature?
> Your visual, olfactory, and auditory senses
> contribute to your hunting skills, and natural defenses.
> I find myself intrigued by your sub-vocal oscillations,
> a singular development of cat communications
> that obviates your basic hedonistic predilection
> for a rhythmic stroking of your fur to demonstrate affection.
> A tail is quite essential for your acrobatic talents;
> you would not be so agile if you lacked its counterbalance.
> And when not being utilized to aid in locomotion,
> It often serves to illustrate the state of your emotion.

(Commander Riker begins to applaud, until a glance from Counselor Troi brings him to a halt.) Commander Riker, you have anticipated my denouement. However, the sentiment is appreciated. I will continue.

> O Spot, the complex levels of behavior you display
> connote a fairly well-developed cognitive array.
> And though you are not sentient, Spot, and do not comprehend
> I nonetheless consider you a true and valued friend.