Embodied Fabrication:
Body-Centric Devices for Novice Designers

by

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Thesis directed by Prof. Michael Eisenberg

We present a class of devices under the umbrella moniker of "embodied fabrication". These devices and the development of the term embodied fabrication is rooted not only in computer science, but in cognitive science, childhood educational theory, emerging digital fabrication technology, and the convergence of these strands present in the do-it-yourself community known as the "maker movement". As such, we operate under a certain set of premises that guide and direct this work. First, that embodied cognition - which places the body at the center of our cognitive operations - provides a framework from which to ground our decisions to design physical peripheral devices as opposed to purely screen-based software. Second, that a strong line of pedagogical research supports providing children with tangible, "manipulative" objects to learn with. Third, that digital fabrication technologies - 3D printing in particular - provide a wonderful new opportunity for children and novice designers in general to make, play, and explore creatively - and that the current design options for 3D printers are not suited to meaningful design and creation of objects by non-expert 3D modelers. Finally, that by following the best traditions of body-centric interaction design for children, devices can be created to provide an educationally and technically rich environment that connects kids to the creative potential of 3D printing. We unpack these ideas more in the introduction, followed by an overview of three prototype devices belonging to this class of "embodied" interfaces, a chapter on related work followed by a chapter on the three user studies we performed with our devices, a discussion of the presented studies, and finally we present a vision of the future of this work and of embodied fabrication devices as a whole before concluding.

Dedication

This work is dedicated to Red Burns, for the opportunity, the honesty, and the paper-smacking. The world is a duller place without you. Thank you.

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I was incredibly fortunate to have found the supporting cast that I did during my studies. My advisor, Michael Eisenberg is one of the true gems of humanity. An unbelievable scholar, gifted writer, and a wonderfully supportive and warm person. Our conversations were always inspiring; may there be many more to come. My father, for putting Mike on my radar as I was applying to grad school and for always letting me know how proud you were. It meant a lot. You and I turned out more alike than I ever would have imagined. My mom, for her unwavering faith that I would be excellent. You were much better at convincing me than I was at convincing myself. Your visits were always a chance to recharge my batteries, feel loved, and be fed extremely well. Monika, for taking the risk of leaving your world behind to join me in Colorado, and for supporting me so well during a stressful time. You're the best cheerleader a guy could ask for. I'm a lucky man. Many others supported this work, academically and socially. Credit goes to Julie DiBiase, Yingdan Huang, and Kate Starbird for their early work on a 3DGeoboard. I owe an enormous debt of gratitude to Nathan Seidle, whose generosity allowed this work to reach its completion. My committee members were all amazingly insightful and supportive. Ann Eisenberg kept the lab from self-destruction more times than I can count. Present and past CU students for their support (especially Jeff and Swamy in CS and all the MFA kids). Lindsay Levkoff Diamond, for being an incredibly understanding and flexible boss during my studies. The DoE and all my friends at SparkFun Electronics - without you, I don't know if I would have made it. Finally, the staff and students at Gold Crown for their amazing support during my user study. Thank you all.

Contents

Chapter

Tables

Table

Figures

Figure

Chapter 1

Introduction

Ten years ago, 3-dimensional printing was solely the purview of large fabrication studios and industrial manufacturing; five years ago the first desktop "homebrew" 3D printers hit the market, though few people seemed to pay much attention; today, desktop 3D printing is one of the big headlines at the annual Consumer Electronics Showcase in Las Vegas, media outlets from Forbes[65] to the Economist[1] are discussing it, and most of the teenagers we talked to during our user studies know what 3D printing is. 3D printing is part of a forceful trend often referred to as the "maker movement"[13], that puts do-it-yourself ethics and emerging technology together in a way that has inspired people the world over to put down the TV remote and pick up a soldering iron. A subset of this movement has focused on "digital fabrication" technology, of which 3D printers, laser cutters, CNC mills, and vinyl plotters (among other devices) belong. Digital fabrication machines take computer-generated files as input and fabricate physical objects from those files. With the help of the maker movement and visionary works on the upcoming age of "personal fabrication"[58], 3D printing machines that once cost tens of thousands of dollars are now available as DIY kits for less than one thousand. Do not misunderstand us - this is a wonderful thing; cost is one, if not the main barrier to the spread of most technologies. However, the maker movement is not without its blind spots. Most innovators behind these desktop 3D printers are of a very privileged socioeconomic background; many of them retired engineers or otherwise possessing technical training far beyond the average person. For the most part, they have not (nor is it necessarily their responsibility to have) truly thought about how to make their low-cost 3D printers accessible to the average Joe and

Sally - much less Joe Jr. - and to be fair, they are not the only actors contributing to the barrier of entry for 3D novices who wish to design for 3D printers.

For those readers who may be unfamiliar with 3D printing, it is indeed what it sounds like - an umbrella term for one of several processes capable of creating 3-dimensional objects (usually fine layers of extruded plastic filament) from digital files, much like a laser printer prints 2D images on paper. 3D printers primarily take in a file format called stereolithography - or .STL for short. Normally, to create an .STL file one needs a rather complicated, professional-level piece of 3D-modeling software, such as Rhino[125] or Solidworks[136]; programs which are rich with features that only seasoned users will find a need for, with sub-menus upon sub-menus and decidedly particular behaviors that any novice - especially a young one - would find quite intimidating. As anyone who has used these software programs knows, one must be very precise and conscious of every operation for a model to turn out properly - and this order of operations is learned slowly (often agonizingly) over time. It is a user interface nightmare; hardly the soft of intuitive environment one might want to learn with. It should be noted that some efforts have been made to create entry-level 3D modeling software - most notably Google SketchUp[135] - although last we checked SketchUp did not export directly into .STL format (there are some rather troublesome looking workarounds however), leaving the average newcomer facing an incredibly steep learning curve in order to produce any original, 3D-printable objects. We emphasize "original" because there are several fairly simple ways to download and print out a pre-created .STL file from the Internet (most notably from the on-line repository Thingiverse[6]).

Although printing out dozens of army men or barnyard animal figurines may be satisfying for a time, and indeed speaks to the compelling nature of 3D printing, it seems fair to say that children do not learn much about 3D modeling from a "download and print" paradigm. Herein lies the crux of the problem - 3D printing offers a wonderfully rich new platform for design, creativity, and exploration, but neither the 3D printer manufacturers nor the companies who produce the software necessary to author files suitable for 3D printing have made accessibility for novices a priority. This is where our journey begins: the desire to democratize 3D printing in a way that empowers

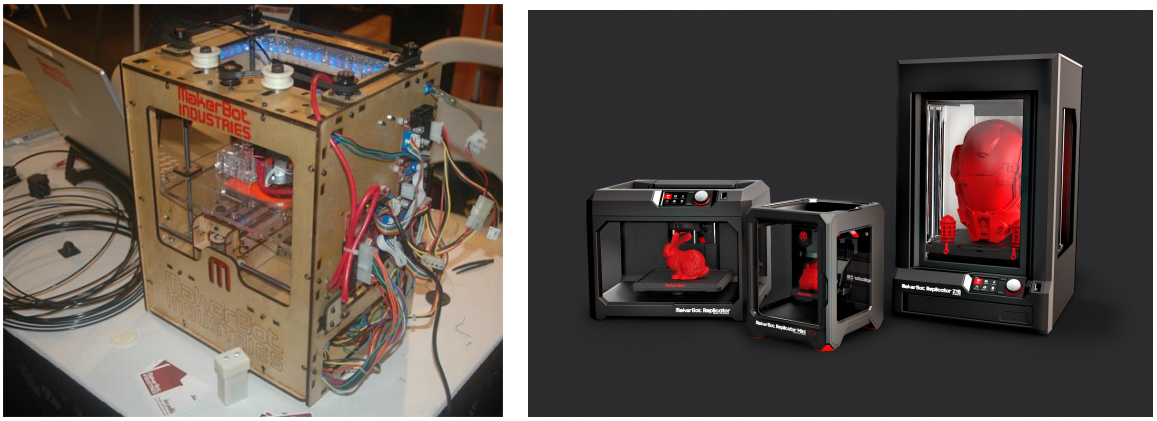

Figure 1.1: Left: One of the first popular desktop 3D printers, the MakerBot "Cupcake CNC", released in 2009. Right: The latest group of MakerBot models, released at the Consumer Electronics Showcase in January 2014.

newcomers, particularly youngsters, in designing their own objects for 3D printing; engaging them in such a way that intuitively introduces many of the core concepts of 3D modeling, while helping to solidify cognitive processes around spatial reasoning and 2D/3D translations, by building a set of devices that act as a new genus amongst an ecosystem of next-generation digital fabrication interfaces.

How, then, did we arrive at the term "embodied fabrication" to describe this new genus? The simple answer, at the risk of over-extending the genealogical metaphor, is that we selected what we deemed to be the best, most relevant traits from a number of related areas (computer science, cognitive science, developmental psychology, pedagogical theory, and digital fabrication technology, amongst others) and attempted to splice them together in such a way as to meaningfully address the issues with 3D printing outlined above.

We derive the term "embodied" from cognitive science, and the fairly recent advances in an area known as "embodied cognition". Embodied cognition posits that our physical bodies and their interactions with the world are more closely bound to our cognitive processes than previously thought. Evidence from research in this area (discussed more thoroughly in Chapter 3 on related work) points to cognitive benefits in basic arithmetic, ratios, proportions, and spatial reasoning -

all of which are useful (if not essential) tools in 3D modeling, simply by involving the body more closely in the learning process. This evidence, combined with the simple intuition that learning the skill of 3-dimensional modeling ought to be done in 3-dimensions as much as possible and not solely on a 2-dimensional screen, provided the impetus for us to look toward a physical solution that involves the body more than a typical piece of software.

Physical, or "tangible" user interfaces are nothing new; wooden blocks have been a part of children's education in a pedagogical sense since the beginning of kindergarten over 150 years ago[57]. Montessori "manipulatives" developed in the early part of last century inspired some of the first attempts at creating physical, computationally-enhanced construction kits for children in the 1980's[123]. Tangible user interfaces, or TUIs have been a growing part of human-computer interaction in a formal way since Hiroshi Ishii's work on "tangible bits"[76] in the mid 1990's, and of course the influence of icons such as Doug Engelbart[49] - one might argue the mouse was the first "embodied" peripheral for a computer, in the 1960's - and Mark Weiser[144] (who presaged many of the devices we take for granted today) as well as many others, should not be overlooked - we give a more detailed account of this lineage when discussing related work. For us, the longevity, breadth of applications, and numerous achievements of mediating human-computer interaction though different physical interfaces further suggests that a tangible user interface, coupled with the proper software is more than capable of providing an accessible and embodied foundation for our work.

Taking design principles from the lexicon of tangible user interfaces, adapting them to better fit an embodied cognition world-view, and focusing on enabling 3D modeling specifically for 3D printers, we designed and built a suite of functional prototype devices for an embodied mode of digital fabrication; hence the title of our work. To this end, we present a class of tangible user interfaces designed to scaffold a child's ability to design, explore, and play in three dimensions, with a particular focus on enabling original output for 3D printing. We present three prototype devices (called UCube, SnapCAD, and PopCAD) as well as piece of companion software that translates the physical actions performed on the devices into screen-based content in real-time.

To give a brief preview of our creations; with their hands, users manipulate a device to specify points (as coordinates in 3-space) that simultaneously display as active dots against a ghosted 3D grid in real-time on a computer. The software on the computer allows for certain modeling operations on this set of input points (e.g., taking the convex hull, making a path through space), exporting shapes to stereolithography (.STL) format with the click of a button, the preferred format for 3D printers, as well as other functionality that we explore more thoroughly in the next chapter.

We propose that these designs form a novel class of embodied input devices aimed at enabling novice output for digital fabrication machines. Over three separate user studies with 11 to 18 year olds, we investigate the ability for children to use our devices to model a given shape (with and without the companion software) and to match configurations on our device to a printed 3-dimensional object (without the aid of the software). In our last study we compare two of our devices over a multi-session study, while also administering a set of spatial reasoning tasks as a pre and post test. We video record the subjects (with parental consent) and analyze the gesture and speech expressions the participants make when explaining a modeling strategy to reproduce a given object.

Through our studies, we show evidence that our suite of devices can be used effectively by young adolescents with very minimal instruction, that a wide variety of shapes can be recreated by the majority of subjects who used our devices, that spatial test scores and modeling performance tends to improve over multiple sessions with our devices, and that the kinds of gestures produced while explaining modeling strategy correlates to modeling success on our devices, a finding which supports prior research on gesture analysis by other authors.

By providing a feedback loop between the bodily interaction with tangible interfaces and the observed changes in real-time on a computer screen, this body of work presents strong new motives for the inclusion of embodied cognition in tangible interface design, while tackling the lack of appropriate tools for novices to create for 3D printers, and evaluating the efficacy of our devices as modeling tools and as devices for strengthening spatial reasoning and cognition. We continue in Chapter 2 to present our prototype devices and the software they operate with, explaining the

evolution of our design choices as well as the technical details behind their operation. Chapter 3 details the lineage of related work, hinted at somewhat in this introduction, drawing connections between the childhood developmental theories and conceptions of space developed by Piaget and refined by Papert, the notions of cognitive development and embodied mathematics discussed by Lakoff and Nuñez, the democratization of digital fabrication technologies discussed by Gershenfeld and Lipson, and the previous adaptation of these achievements into computer science. Chapter 4 is devoted to the evaluation of our work, presenting three user studies, their procedures and results. Chapter 5 delves deeper into the discussions which surround the observations from our studies, comparing them with prior research, and against each other. Finally, Chapter 6 provides a vision for immediate future work on our devices, a more expansive vision of the possibilities inherent in embodied fabrication, and ends with our concluding thoughts.

Chapter 2

Prototype Systems

Over the past several years we have been working on the creation of a family of child-friendly tangible user interfaces that would serve as input devices for exploring 3D modeling and digital fabrication in an "embodied" fashion. As discussed in the first chapter, the motivations behind this work are thematically diverse, but can be distilled as an attempt to create a more intuitive, body-centric way for novices to design for 3D printing while also strengthening a sense of spatial translation between 3D and 2D (screen based) representations. To this end, we have created three prototypes: the UCube, an initial proof-of-concept device using simple components, SnapCAD, a more expressive and capable iteration of the UCube relying on magnetized LED circuit boards, and PopCAD - a paper-based interface addressing several of the cost and portability concerns raised by SnapCAD. These systems all communicate with versions of a companion software program running on desktop computer. This chapter describes (in chronological order) the development of these three systems, the software that interfaces with them, 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". 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 initial design goal 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 manipulations on a device into a software program that could display the actions performed on the geoboard in a "meaningful" way - that is, in a way that could potentially extend spatial reasoning abilities between the 3D representations created on the device and the 2D, screen-based images displayed on the computer screen. Credit for early work on this idea is due in part to Julie DiBiase, Yingdan Huang, and Kate Starbird, who outlined the idea of computationally-enhanced mathematics manipulatives, including the geoboard, in an earlier work from our lab[45][138].

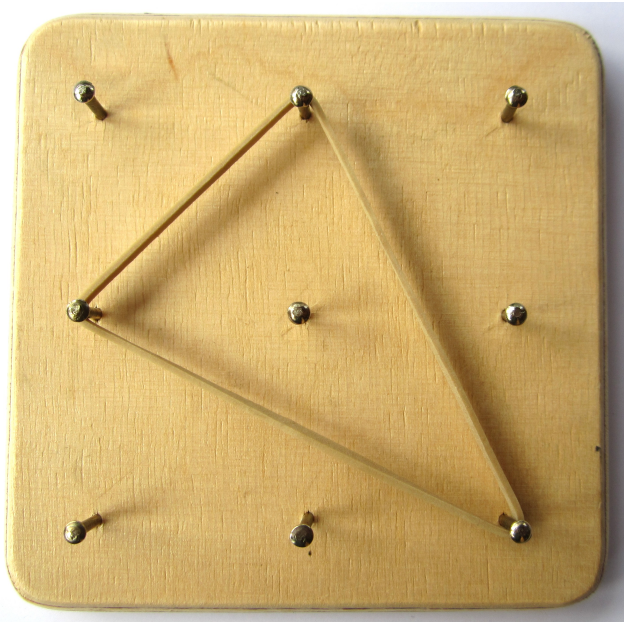

Figure 2.1: A simple 3x3 geoboard, with a rubber band stretched around several pegs, forming a triangle.

The UCube (as seen in 2.2) is 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 grid of 4x4 evenly spaced nodes or sockets, which act somewhat like the nails in the 2D geoboard. The towers themselves contain four switches placed vertically along the tower, creating a potential for 64 (4x4x4) distinct points to be activated. The towers are "plugged in" when placed into one of the 16 socket nodes, connecting them to the underlying circuitry responsible for providing power to the towers and relaying the state of each of the switches to the computer, via an Arduino Mega[99] microcontroller. 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 to a piece of software on the computer. An abstracted illustration of the hardware system is seen on the right in 2.3.

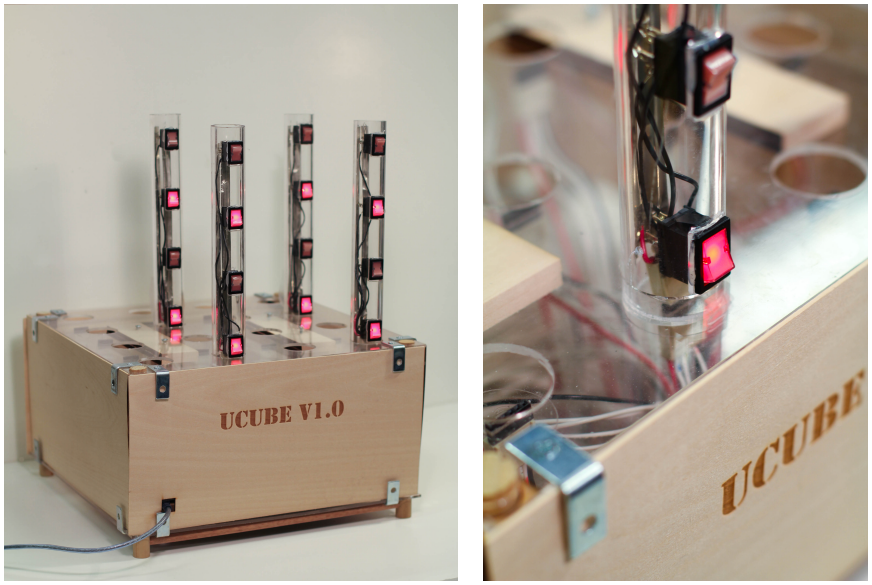

Figure 2.2: Left: The UCube device, with four towers and eight lit switches, representing (in one instance) the eight vertices of a cube. Right: A detail view of one of the towers placed into the UCube modeling board with the bottom switch lit.

Figure 2.2 shows two views of the UCube interface. The picture on the left shows the device, with four towers placed in an evenly spaced square, with two "board units" separating each tower. The lowest and third-lowest switches on each tower are lit, marking eight active points. Thus we have eight active points, spaced evenly in such a way to describe a cube of two "board-units" in length if we were to take the convex hull of those points. The photo on the right gives a detailed

view of the UCube hardware. A tower has been plugged into the board and its bottom-most switch turned to the "on" position, indicted by the glow of the LED behind the switch.

The UCube software (discussed more thoroughly later in the chapter) takes the incoming coordinate data from the microcontroller embedded in the device and translates that data into a real-time visualization on the computer screen. The graphical user interface centers around a "ghosted" grid of all the potential points, with the active points highlighted. The software interface 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 are explained more thoroughly in the software section later in the chapter, but we give a brief list here so as to clarify our purposes: taking the convex hull of the point set (as imagined in 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.

2.1.1 Technical Implementation

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 is a clear 1/4" acrylic square, into which a four-by-four grid of circular holes has been laser cut in such a way that the towers fit snugly. This layer of clear acrylic acts as a brace to hold the towers upright, helps guide the pins from the tower into alignment with the socket into which they must be placed, and ensures that the towers themselves are resistant to being knocked over.

The next layer down holds a set of headers, six per socket (one each for power and ground, and four input lines, one for each switch on the tower), 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 header wires connect directly

to the breadboard, where each switch circuit runs through a 10KΩ resistor, and then to a digital input pin on the Arduino. When plugged in, the Arduino is able to communicate (via asynchronous serial communication) the set of active switches (and corresponding coordinates) to the computer through a USB cable. 2.3 depicts a schematic diagram of the UCube hardware.

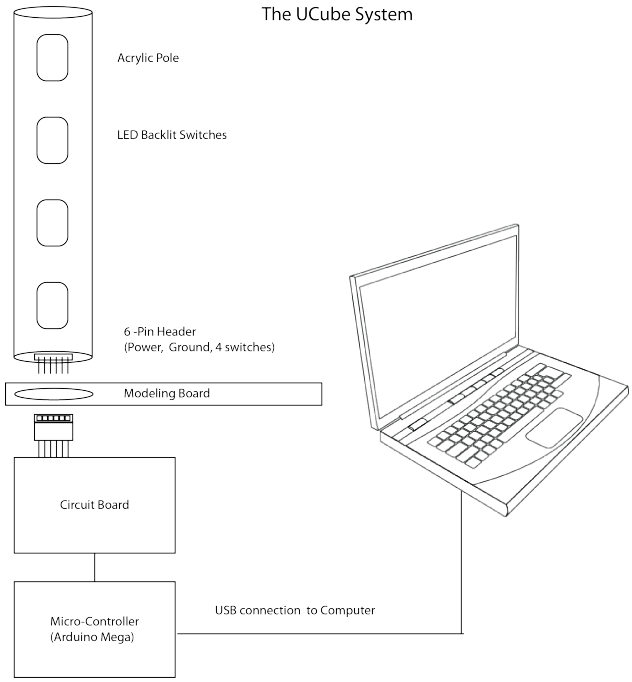

Figure 2.3: A schematic illustration of the UCube hardware.

The towers are roughly nine inches tall, made of transparent acrylic, cut from a circular tube with a 1" interior diameter (1.5" exterior). The towers were laser-cut in order to house the four switches and corresponding circuitry elements. Four rectangles are laser-cut along the face of each tower in such a way to allow the back of each switch to be placed inside the tower while the faceplate remains on the surface. The switches are back-lit (when switched on) with built-in red LED's. Each switch has a 270Ω current limiting resistor soldered between two of its legs to protect the lighting element. Headers were soldered on to the power and ground pins of the switch, which connect to a strip of silver conductive tape affixed to the back of the inside of the tower (one can make this out somewhat in Figure 2.2). The signal line from each switch (responsible

for letting the microcontroller know the switch state, either on or off) is soldered to a wire which reaches down to a six-pin header at the base of the tower. As the switches are lit when active, it becomes apparent which points are on as well as giving a more accessible "gestalt" of the shapes being modeled. The luminosity 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.

2.1.2 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; then, by placing two more towers and creating the same triangular shape "shifted over" by two units (as seen on the left of 2.4) 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 (as seen in the center of 2.4), 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 on the right in 2.4.

2.1.3 Limitations

The astute reader will have picked up on some of the more obvious limitations of the early system: as a three-dimensional modeling device, it is quite limited in the scope of things it can effectively model, certain geometric shapes are impossible to model on an integer lattice (a do-

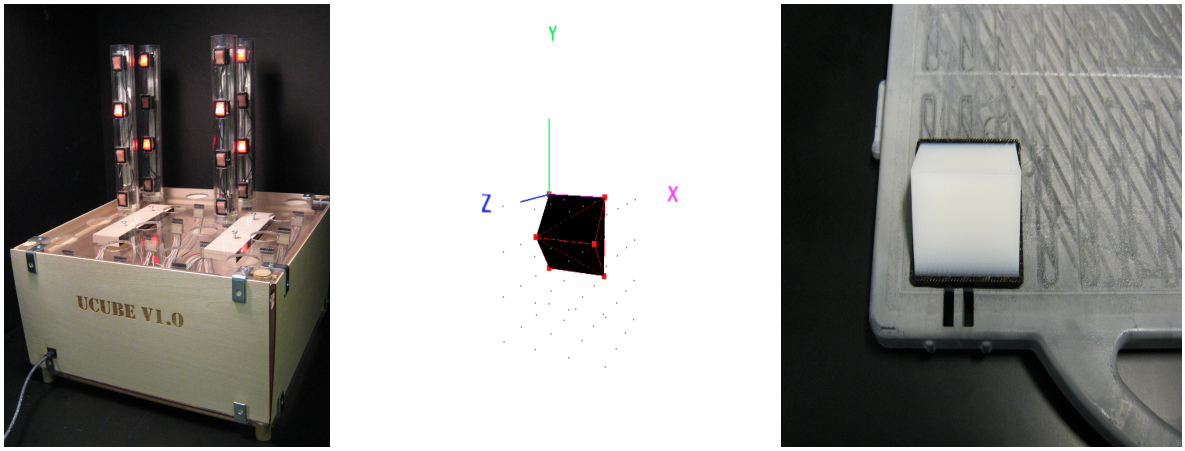

Figure 2.4: Left: The UCube device, with four towers and six lit switches, representing the six vertices of a triangular prism. Center: An early version of the UCube software, representing the convex hull formed with the six active points from the picture to the left. Right: The resultant 3D print, exported from the software to a 3D-printer friendly format.

decahedron, for instance), a 4x4x4 resolution is clearly insufficient for complex shapes, and the inability to create curved surfaces precludes most "natural" objects (such as human faces) from being represented in a life-like manner. It is thus important to differentiate this system (and the others mentioned in this chapter) from a "professional" 3D modeling system; our focus is on ease of use for novices, to provide a visual and tactile bridge between 2D and 3D worlds, and to provide a simple way to create shapes suitable for 3D printing. Even so, this does not preclude us from attempting to make a more powerful, expressive, and stable interface to present to users.

2.2 SnapCAD

Based on the limitations of the UCube mentioned in the previous section, and observations from the two user studies we performed with the UCube (discussed in chapter 4), we designed a second, more powerful device named "SnapCAD". Formerly known as UCube v2, this next generation interface consists of a total input space of 7x7x7 points, forming 343 distinct coordinates (as opposed to the 64 points of the UCube). We focused on two main design goals with the SnapCAD: greater expressive power and greater stability in the system operation.

2.2.1 Technical Implementation

To start with system stability, then; custom printed circuit boards replace loose wires, the towers are 11" tall, designed in Rhino[125] and 3D printed in ABS plastic to safely and securely house the towers, which are in fact printed circuit boards of their own. Instead of a rickety housing, the top layer is 1/2" acrylic which was milled on a CNC machine to precisely fit the newly designed towers. The sides and bottom are hand-crafted wood, with channels cut to allow the top and circuit board layers to easily slide in and out. The frame is not glued on one side to allow for repair and maintenance. This side is secured by custom metal brackets and screws. Each socket has its own printed circuit board, held firmly in place by zip ties around a latticed acrylic layer underneath the boards. The system has since traveled to the Denver Art Museum, the Computer Clubhouse in Lakewood, Colorado, and ridden around in the back of several cars without mishap (not to mention roughly 20 hours of user testing by eager adolescents).

Figure 2.5: Left: the SnapCAD interface, showing four towers with two red LEDs each, arranged in a cube-like configuration (as imagined earlier with the UCube). Right: a detail of the SnapCAD hardware - the PCB tower is housed in a 3D-printed shell, which plugs into one of a chained set of shift-register boards. The LED boards snap on to the towers via conductive magnetic snaps.

The goal of greater expressiveness was met in two ways; by increasing the possible input space from 64 points to 343, and by designing a system that allowed for each point to be activated by more than one color of LED - effectively allowing for multiple shapes to be modeled at once, or multiple "players" to interact with the board at once. Both of these solutions required changes in hardware

and software from the UCube. Working on the scale of multiple hundreds of inputs necessitated the design of custom circuit boards to relay information effectively to the microcontroller. The Arduino Mega has only 54 digital input/output pins, far too few to assign each line directly to an input, even if one wanted to deal with tracking 343 i/o lines (which we most certainly did not). Instead, we designed a circuit board around an input shift register chip from Texas Instruments - the CD4021BE - that could effectively provide eight more input lines per chip and operate with the Arduino's ATMega 328 Serial Peripheral Interface (SPI) protocol, which requires only three lines from the Arduino. By breaking out the pins on the CD4021BE so that they could be chained together (by aligning the serial output of one chip to the serial input of the next chip, while also passing along the latch and clock signals, the other two lines necessary for the SPI to work)[1] . By arranging 49 of these daisy-chained boards in a 7x7 grid, we had the framework to read in from 343 inputs in real time. Only one more problem had to be solved: at around 35 connected shift registers, we exceed what is called the "fan-out" of the Arduino microcontroller - the number of connected input gates that a given pin on the Arduino to drive a current load into. To get around this problem, the clock and latch signals are put through a set of two "buffers" - in our case CD4049BE inverting hex buffers - which can used for logic level conversion (the inverting part, which we do not need, hence the second inverting buffer), but also as a "boost" to drive the signal farther. One set of buffers was enough to get our signals to the computer reliably.

This change in scale also meant rewriting most of the modeling software to effectively handle the greater expressiveness of the physical system. The astute reader may have noticed that while the CD4021BE adds eight inputs per board, our system calls for a 7x7x7 array - so what were we to do with the extra input? The dilemma actually ended up solving several problems; in the UCube firmware each input triggered an (X,Y,Z) coordinate to be send out the serial port - by switching to shift registers over SPI, we are limited to one character per input - either a 1 or a 0. Normally, a serial string can be delimited in software by looking for certain characters at the

[1] We understand this section is somewhat technical. A great introduction to using shift registers in this way can be found at: http://www.arduino.cc/en/Tutorial/ShiftIn

beginning or end of a communication, and parsed accordingly, but we only had a string of 343 0's and 1's. Given that most of the sockets would be returning a zero most of the time, by tying the 8th input line high we could count characters and check for a "1" every eighth character to ensure the serial string was correct - and since we were isolating this character anyway, it was simple to throw it away afterwards and thus be left with only the sets of seven digits describing the state of the inputs. The problem of generating the proper coordinates from the input stream was then a matter of creating a "lookup table" where the *nth* character in the input string array was the *nth* element in an array of 3D coordinates.

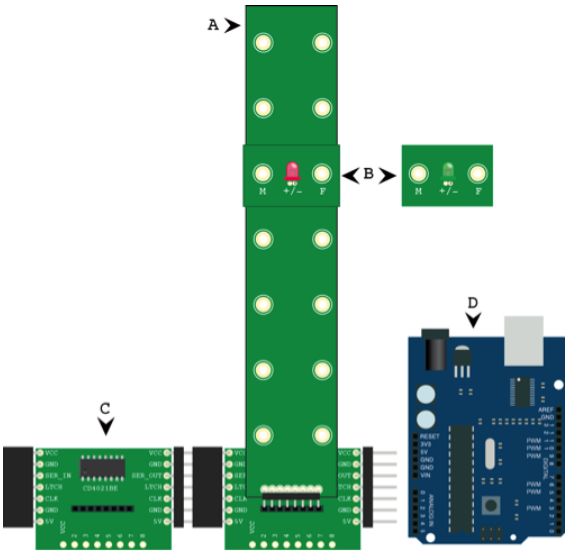

Figure 2.6: A schematic of the SnapCAD technical design, showing a sample tower (A), LED light element (B), shift register board (C) and Arduino (D). The Arduino microcontroller's role is to send coordinates (and colors) of the LED lights, once placed, to a desktop computer. A fuller description of this schematic is provided in the accompanying text.

The other enhancement to the expressive power of the SnapCAD design is the ability to use each socket in each tower with more than one color of LED. In in order to make this a possibility, we had to find a way to make the LEDs detachable from the tower and "swap-able" with other colors. This was achieved by soldering conductive magnetic snaps directly into the circuit boards themselves; the magnets act to both attach LEDs to the tower, but also to close a circuit and light

up the LED. We used snaps and not just simple magnets because LEDs are polarized - they have only one correct orientation - and snaps have a male and female part that could be used to indicate the correct orientation. This multi-color capability can be seen in Figure 2.7.

This ability to swap out different colors of LEDs 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, and imagined a sample scenario, explained in the next section. The SnapCAD version of the software includes this "multi-payer" ability as well as some additional changes that 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 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.

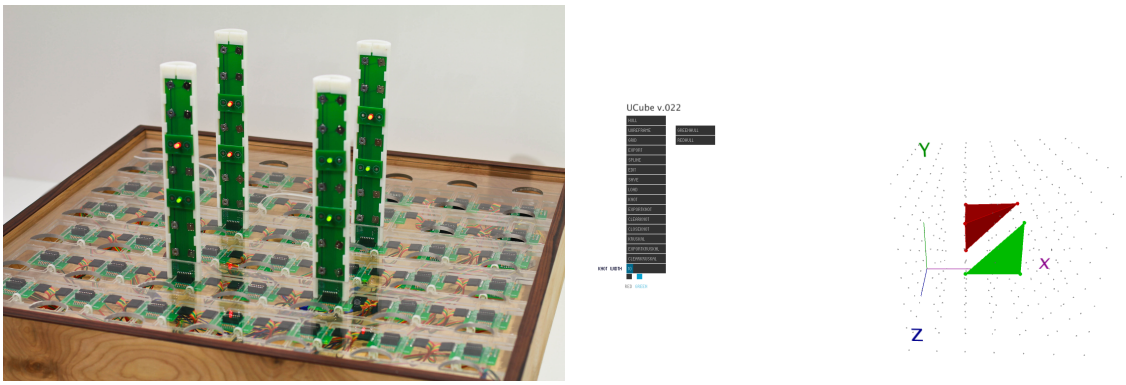

Figure 2.7: Left: The SnapCAD software showing two convex hulls of different colors. Right: the SnapCAD software showing a minimal spanning tree model.

A note on the 7^3 array in SnapCAD: in our user studies with UCube, 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.

2.2.2 A Sample (Red/Green Player) Strategy Game for SnapCAD

In this use case, we make use of the two-color capability of the SnapCAD to suggest a hypothetical game, or genre of game, that could be created with the system. The imagined game in question is a geometric strategy game between two players, "Red" and "Green". At the outset of the game, each player is given four lights of her own color; the two of them are told to place their lights at the eight corners of a cube in the positions shown in the photograph shown in Figure 2.8 on the upper right.

Now, the computer could display the convex hull of the present set of lights (a cube), as shown in Figure 2.8 on the upper left; and then (in our scenario) the computer tells the Green player to move one of her lights to create the new convex hull shown at the bottom-left of Figure 2.8. Thus, the Green player's job is to change the "cube" hull to the new hull with one move of one green light. A correct answer to this challenge is shown in the photograph of Figure 2.8 at the bottom-right; and if the Green player makes this correct move, the Red player is now given the (current) convex hull and yet another hull that could be created with one move of a red light. In this fashion, the two players take turns moving lights of their own color to produce a new overall configuration of lights at every step, until one player fails to solve the current challenge, at which point the game is over. There are, of course, many variants or extensions of this game that could be imagined (for instance, a player might be asked to shift two lights, or to add a new additional light in her color, to create a new convex hull). The purpose of this example is simply to show that, with the inclusion of two available colors for spatial points with SnapCAD, a sizable potential landscape of geometric activities and puzzles becomes feasible.

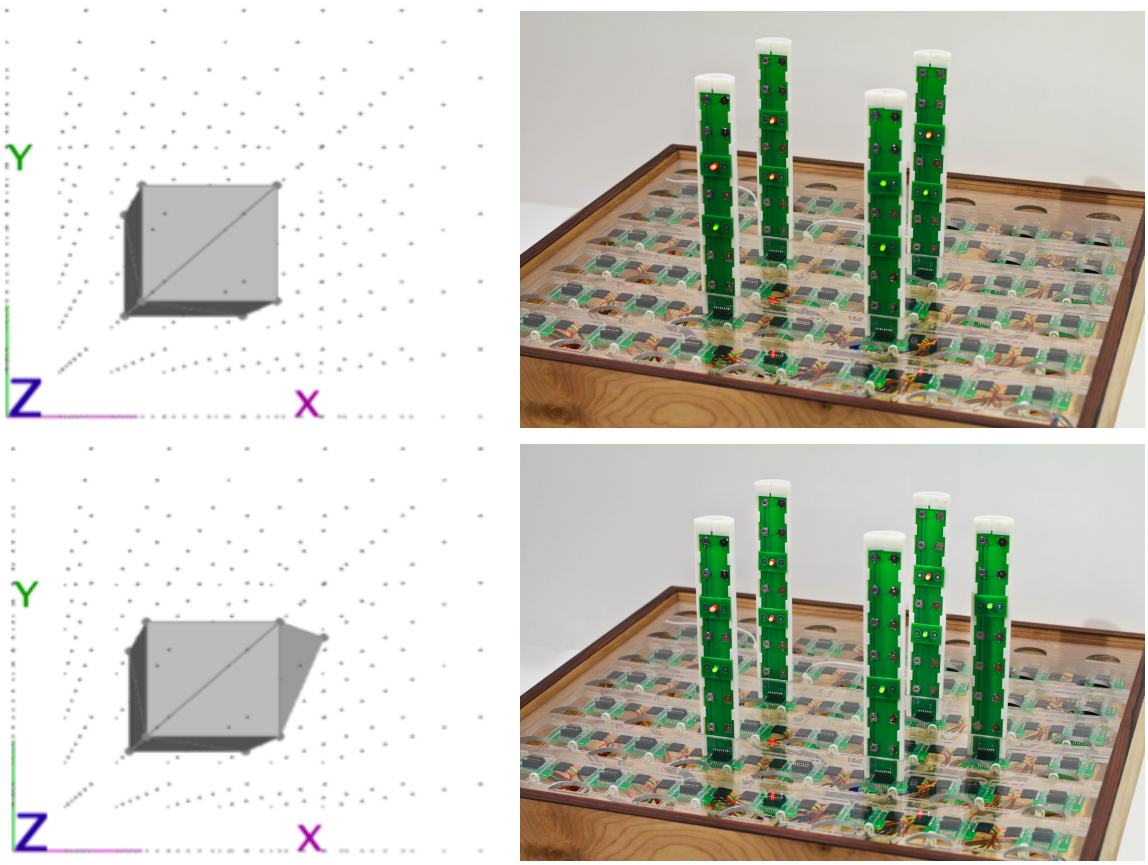

Figure 2.8: Left: The SnapCAD software showing two convex hulls of different colors. Right: the SnapCAD software showing a minimal spanning tree model.

2.3 PopCAD

Our motivations for creating a third, alternative interface 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 to produce or

purchase; it is also rather unwieldy and unportable - it is moderately heavy, fairly large (over 30 inches square), and has many separate pieces (like the towers and LED boards) 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 electronic components such as copper or conductive tape and conductive inks. In recent years, revolutionary work has been done in combining electronics and paper crafting[117][100], 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. We will cover the two paper-based prototypes we created in this vein, dubbed "PopCAD v1" and "PopCAD v2".

2.3.1 PopCAD v1

For the initial prototype, we use a simple construction paper as it provides 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 three 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, in the form of a flat copper-based adhesive tape. 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 this first version, 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

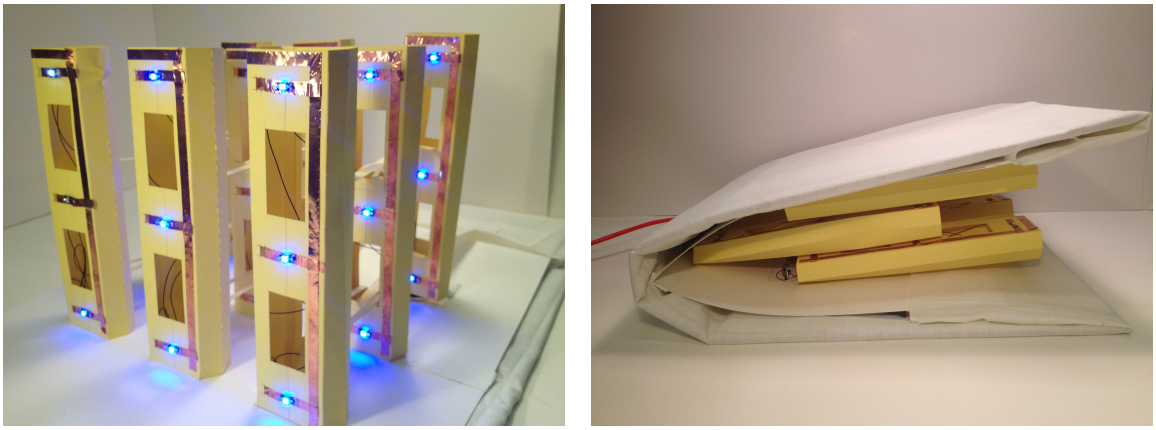

Figure 2.9: Two views of the first pop-up book prototype, showing the interface in both open and closed states.

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 copper tape circuit of three LEDs, three switches, and ground. These seven wires are then 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.

2.3.2 PopCAD v2

Although the first PopCAD iteration was a fully-functional prototype, as we approached user testing with the PopCAD it became apparent that there were several compelling reasons to iterate on the original design. Through a few informal user evaluations as well as our own reflections on the device, we identified several key issues that could be improved upon: (a) the paper engineering design, (b) the structural integrity of the book as a whole, and (c) the lack of "paper-ness" with

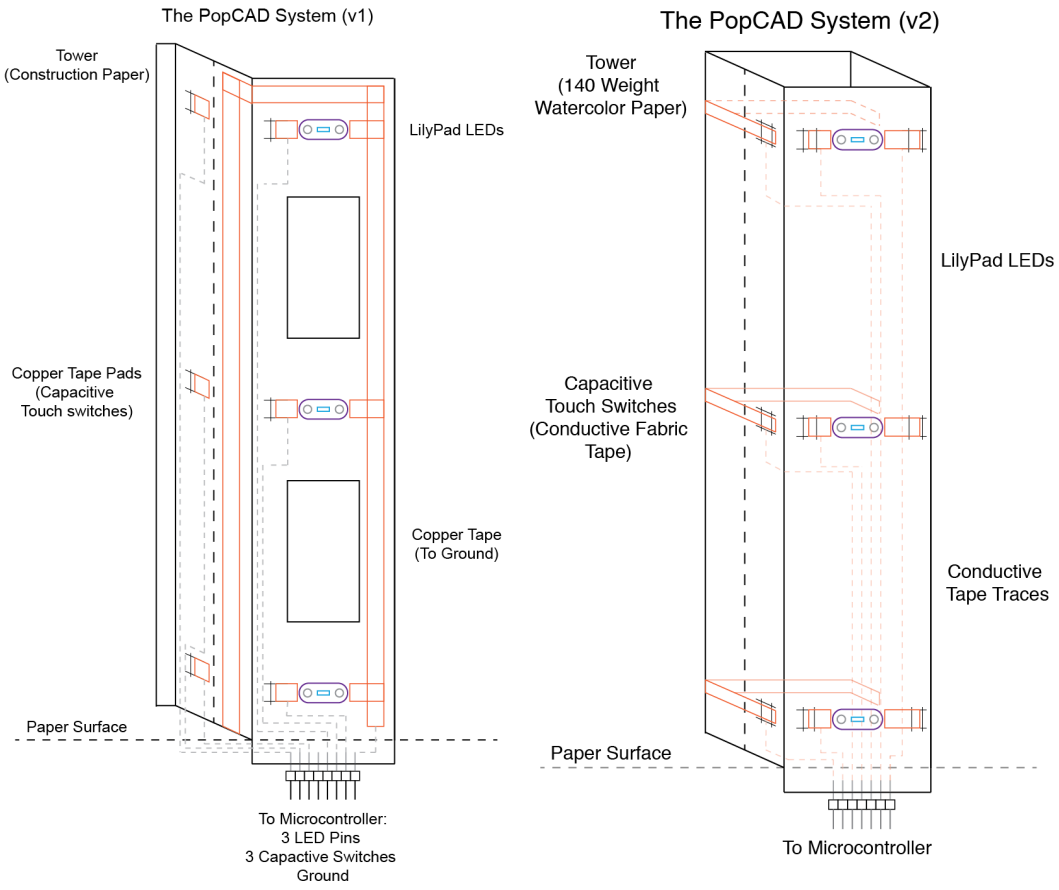

Figure 2.10: The two PopCAD designs side-by-side: PopCAD v1 (left) uses copper tape and 30 gauge wire for the paper circuit, while PopCAD v2 (right) uses fabric-based conductive tape without needing any wires. PopCAD v2 also removes the need for large rectangles to be cut out of the paper tower for the paper strut mechanisms.

respect to the circuitry and electrical components of the design.

To start with the first point above, then: a look at the initial design of the pop-up mechanism reveals the presence of horizontal paper "struts" connecting the towers in the middle column (along the center crease) to their counterparts on either side. These struts were necessary in order to generate a pop-up motion from the middle of a book and force each tower upright. The mechanism was successful; however, the struts directly interfered with the ability to reach many of the conductive tape switches. In version two of the PopCAD, the struts were removed in favor of a pull-tab system whereby each row of towers is raised and lowered by a tab at the front of the row

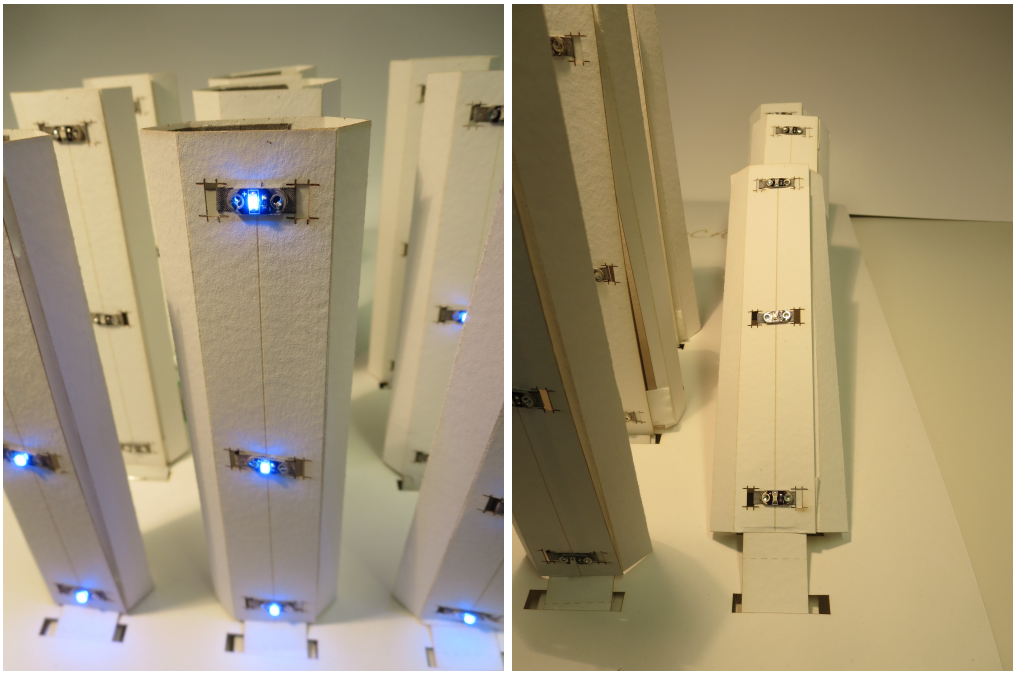

Figure 2.11: Two views of PopCADv2 design: with towers raised and LEDs lit (left), and with the rightmost column of towers laid flat (right).

(the pull tab system can be seen in Figure 2.11).

We were concerned about the overall stability of the first prototype; lights would sometimes fail to operate properly, the horizontal struts kept breaking, parts of the towers were weak, certain points in the wiring were weak, and the opening and closing of book (and thus the folding of the towers) put enough strain on the circuitry that we were concerned whether it would survive a user study. The second prototype addresses these issues in several ways: first, we use a heavy watercolor paper (140 weight) for all the paper engineering, making the towers and the pull-tab mechanisms more resilient to repetitive use. Second, we replace the copper tape, which has a tendency to break over heavy creases, with conductive fabric tape, which resists repeated creasing much better, and finally, we made adjustments to lessen the strain on the towers and the circuitry, by minimizing stress points and reinforcing known weak spots.

In the first prototype, we still used traditional jumper wires from the Arduino to connect to the headers beneath the towers, and 30 gauge wire (still traditional) inside of the towers to connect

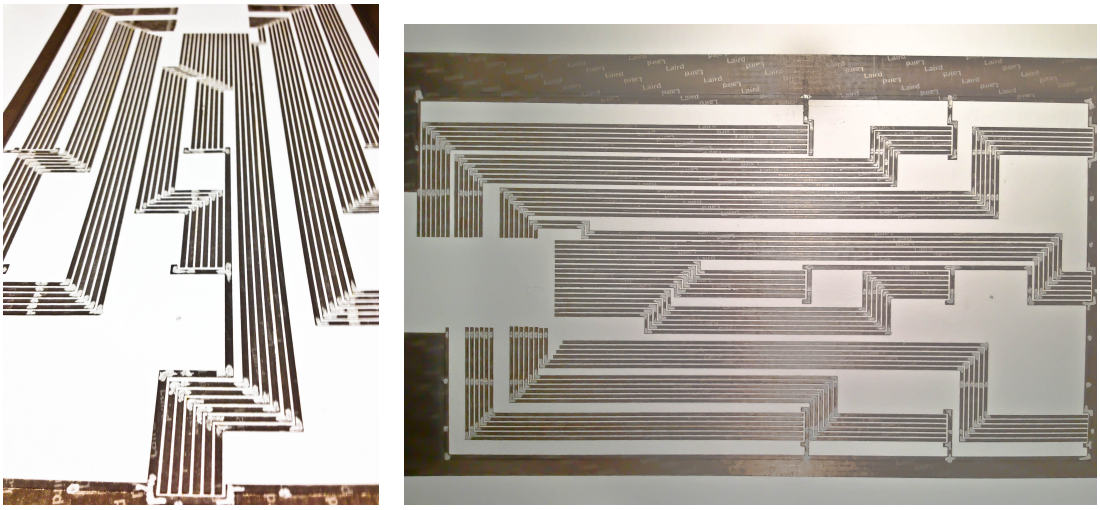

Figure 2.12: Two views of the conductive tape circuit connecting the paper towers to the Arduino Mega microntroller. The circuit was constructed by laser cutting a design through conductive tape (but not through the paper beneath it) and removing the excess material.

from the headers to the LEDs and copper tape. Admittedly, this does not feel very "book-" or "paper-" like, or in the spirit of faithfully exploring paper-based electronics. PopCAD v2 has no traditional "wires" at all. Instead, we use a fabric-based conductive tape, which, besides laying flush (unlike wires) and feeling more like paper than copper tape, the fabric tape is (unlike copper tape) able to be used in the laser cutter in our lab. Figure 2.12 shows two views of the PopCAD v2 circuit, constructed by placing strips of the conductive tape on watercolor paper, using a laser cutter to etch a circuit diagram through the tape (but not through the paper), and peeling away the excess tape, leaving the desired traces of tape. This technique allows us to create a precise yet completely flat circuit layout. The accuracy of this method permits the Arduino Pro Mega (a thinner version of the regular Arduino Mega) to be affixed directly onto the paper. The towers use this conductive fabric for the capacitive touch sensors as well as material to solder the LEDs to, eliminating all the standard wires from our design.

The software for the PopCAD retains all the algorithmic capabilities of the SnapCAD version of the software (convex hull, path, minimal spanning tree), but as the LEDs are affixed to the towers, we lose the ability for multiple player functions. However, it should be noted that this was in part

intentional; we did not want any loose parts that could easily break, get lost, or other make the device less portable. As it stands, the PopCAD (unlike its predecessors) is self-contained as one piece, is small and light enough to be carried with one hand, and is considerably less expensive (and less time-consuming) to produce. We offered sample use cases for the previous devices that involved descriptions of various technical features; for the PopCAD it seems more appropriate to instead paint a more general user scenario that speaks to the intent behind PopCAD's design. Imagine an art teacher, girl scout troop leader, hackerspace or FabLab member, or any number of educators either wondering how to get into this "3D printing thing" or who have a MakerBot sitting in a corner gathering dust. They find plans on-line (perhaps on Instructables[74] or some similar DIY-oriented forum) for a relatively cheap, portable device that they could not only turn into a group project to build with their kids, but once built would offer a new way to introduce children to 3D modeling and 3D printing in a completely new way. The democratization of digital fabrication technology is (as stated earlier) a core goal of this work, and in many ways the PopCAD is the device that embodies this ideal the most. So while it may be less expressive or powerful in some ways (though as we point out in later chapters, this can sometimes be an advantage), the PopCAD does have a place in our suite of devices.

2.4 Software

The software for the aforementioned devices utilizes the serial communication library for the Processing[115] programming language (essentially a sub-set of Java) to read in the active coordinates from an Arduino microcontroller; it then displays those coordinates on-screen as larger points against a "ghosted" grid of grey dots. The exact methods used to achieve this varied by device, and were detailed in the device-specific sections above. This on-screen model can be manipulated in a number of ways. Clicking and dragging along any axis rotates the model, as does the use of the arrow keys on the keyboard. Holding the shift key while performing either action moves the entire model around the screen (essentially re-centering it). The "control" key plus an up or down arrow key zooms in or out along the z-axis. In addition to camera movements, there

are a limited number of functions represented by a simple graphical user interface which aid and expand the modeling capabilities of the connected device.

For a brief overview of these functions, then: there are three ways of interpreting the active set of points on the connected device: by taking the convex hull of the input set, by connecting each point sequentially with a 3D path, and by connecting the set according to a minimal spanning tree algorithm (more on these modes soon). There is a single "export" button that will take whatever the active shape is, no matter the mode (if there is one) and generate a stereolithography file (.STL), the standard file format for 3D printing, although .STL files can also be opened by more sophisticated 3D modeling software, providing the possibility for the software to be used as a sort of "sketchpad" for rough ideas or shape that can refined afterwards. There is a "close path" button which will connect the first and last segments in an open path (e.g. in constructing a square path, after the fourth point has been placed, there will still be an open side of the square - pressing this button will complete the square). There is an "edit" mode, whereby the real-time input from the device is suspended in favor of being able to click-and-drag the active points around with the mouse. Consequently, there is a reset button, in the case that the user wishes to "snap back" to the normalized integer lattice. There is also a slider element entitled "path width" that will dynamically adjust each segment or branch width when in path or tree mode, making the segments "skinnier" or "fatter". Finally, two minor aesthetic options - the "wireframe" button will turn off the "fill" of the shape, showing the outline stroke with a transparent fill, while the "grid" button will toggle the visibility of the ghosted grid of non-active points.

As a guiding heuristic for our software design, it should be noted that the device software is intentionally minimal. Our aim is not to produce another sophisticated software modeling program - there are plenty of good ones available already. Instead, the software is meant to aid the user in clarifying their physical actions with the physical device, while maintaining a low barrier to entry, a great possibility of expressiveness, and multiple ways of approaching any given exercise - a trio of design heuristics often referred to by Resnick (and others) as low floors (accessibility), high ceilings (expressiveness), and wide walls (multiple paths)[124].

2.4.1 Modeling Modes

This section will describe the three main modeling modes of the software, with particular attention to explaining the methods by which they form shapes, the algorithms behind how they operate, and the modeling domains for which they are particularly suited.

2.4.1.1 Convex Hull: Creating Polyhedral Forms

In observing a set of lights placed on an integer lattice in 3-space, one of the first mental images we thought of was to take the convex hull of that set and create a solid polyhedral form. One may think of the 2-dimensional convex hull as the operation performed on the 2D geoboard mentioned earlier in the chapter; given a randomly scattered set of nails in a board, the convex hull of those nails will be equivalent to a rubber band that stretched around all the points. That is, the minimal form that includes all of the line segments connecting each pair of points, as the rubber band forms a straight line between those nails on the hull as opposed to curving inward (thus the minimal shape of line segments as opposed to area). In three dimensions, this becomes a convex polyhedron instead. Many popular 2-dimensional convex hull algorithms originated in the early 1970's (e.g. Jarvis March/Gift Wrapping, Graham Scan), while a 3-dimensional solution was published in 1977[113] and popularized by the same author in the book, **Computational Geometry: An Introduction**[114].

The version implemented in our program is a derivative of the work presented in [22], and adapted from the implementation at [94] which combines a 2D QuickHull Algorithm with a general dimension Beneath-Beyond Algorithm to achieve a general dimension convex hull solution. In brief, the strategy works as follows: (a) from a given set of input points, where the coordinates are known, create an initial 3-simplex (tetrahedron) - from the min/max points in along each dimension (x,y, and z), and add the four faces of the tetrahedron to the stack, (b) Pop a face from the stack and get the point most distant to that face, (c) Find all faces adjacent to the selected face, find the horizon edges of the adjunct faces and extrude the shape along those edges to the selected point. (d) Put

the newly discovered faces on the stack and repeat from (b) until all points have been accounted for.

When the hull mode is active in the software, the coordinates on the connected device must be sent to the hull construction methods each time a point is added or removed to ensure that the hull remains accurate in real-time. The worst case for this algorithm is $\Omega(n^2)$, although in practice is not worse than $\Omega(n\ log\ n)$. Figure 2.13 shows two screenshots of a "before and after" convex hull computation in the software in which the picture on the left in simply displaying the active set of points, while the figure on the right shows the interpretation of those points after clicking the convex hull button.

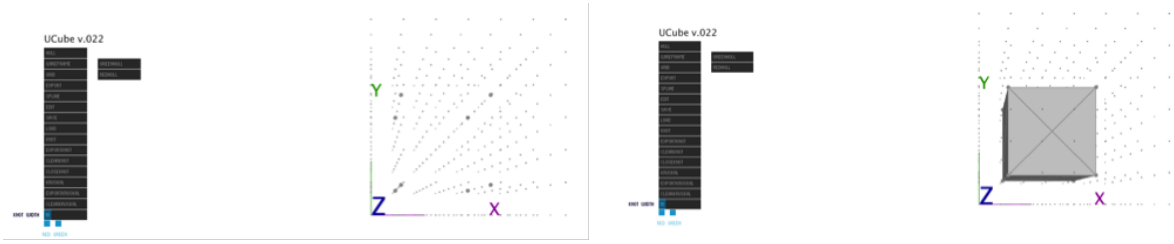

Figure 2.13: Two screen views (left and right) of the device software, illustrating the way in which the software displays the convex hull of a cube. Left: The set of eight input points, before the "Hull" button has been pressed. Right: The resulting convex hull, forming a cube from the input points.

Polyhedral forms obviously have a long history not only in modeling, but in geometry (the Platonic solids), architecture (the Pyramids of Egypt), and numerous other disciplines over the ages (building blocks, paper crafts, etc.). Though not all the Platonic solids can be modeled naturally (i.e. without edit mode) on our devices, certainly pyramids can be, as well as other common convex polyhedral shapes (e.g. a canonical "house" consisting of a cube with a tetrahedron sharing the cube's top face). Some examples are shown in Figure 2.14 below.

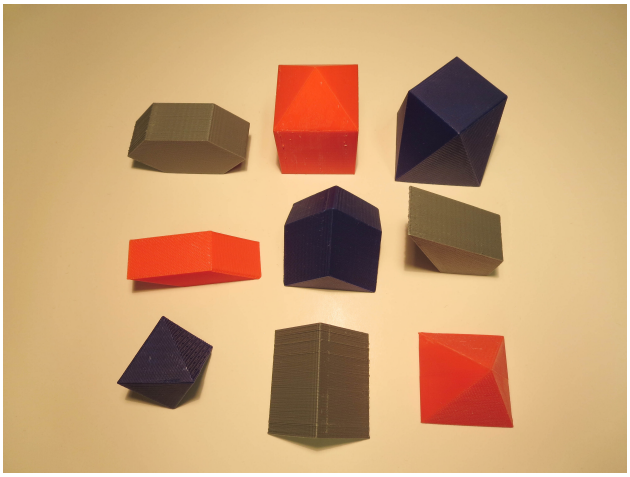

Figure 2.14: A collection of 3D printed shapes modeled using the convex hull mode in the software with the devices mentioned earlier in this chapter.

2.4.1.2 Paths: Creating Linear Forms and Knots

In the convex hull examples in the previous paragraphs, we have not made use of the fact that the software samples selected points in real time: thus, when a user adds or subtracts a point in space, that change is registered immediately in the desktop software. What this means is that the user can exploit not only the overall set of selected points, but can also make use of the **order** in which those points are selected. A sequence of selected points need not represent only vertices of a solid; it can also represent a path over time in 3D space. Figure 2.15 shows several sample projects based on this idea. Here, the software has been employed to read points as successive positions of various routes through 3-space. The resulting paths have been printed out on a 3D printer.

In some cases, the path is closed, finishing at the same location where it started; the path printed out at center in red in Figure 2.15 is in fact a well-known mathematical form, a trefoil knot. (It may be worth mentioning here that such a knotted form would be rather tricky to create in standard 3D modeling software, but the form can be created "by hand" with our devices, selecting light positions in space along the path of the knot.)

To briefly explain the workings of this mode, then: each point on the device is stored, in

Figure 2.15: A collection of paths modeled on our devices using the path mode in the software, exported from the software and 3D printed in our lab. The red shape in the middle may be recognizable as a traditional trefoil knot.

order, in an array. Once the second point of the path is added (one point a path does not make), each point is then "exploded" into a cube, centered on the point. The size of each cube is controlled by the "path width" slider, so the single original point generates 8 points, offset by the current value of the path width slider (e.g., Point p1 = new Point(x + offset, y + offset, z + offset);). The algorithm then takes the cube of points associated with each pair of connected points (e.g., points 0 and 1, 1 and 2, 2 and 3, etc.) and runs the convex hull algorithm discussed earlier, generating a sort of rectangular prism between the two cubes. By connecting each new point to the previous one, a trail of rectangular prisms is generated between the points specified, in the order in which the user placed them. Figure 2.16 shows a trefoil knot created with the path mode. By highlighting the strokes in red, one can see that each point is in fact surrounded by a cube, while each cube is connected to its neighbors by rectangular prisms.

The utility in creating a mode like path is fairly self-explanatory; it allows for a vast number of shapes to be modeled, of a wholly different class of objects as the traditional polyhedral style of the convex hull output. As we will discuss in greater detail later, this method was popular with children who used it; in some ways it is akin to writing or drawing, albeit in 3D, where once you

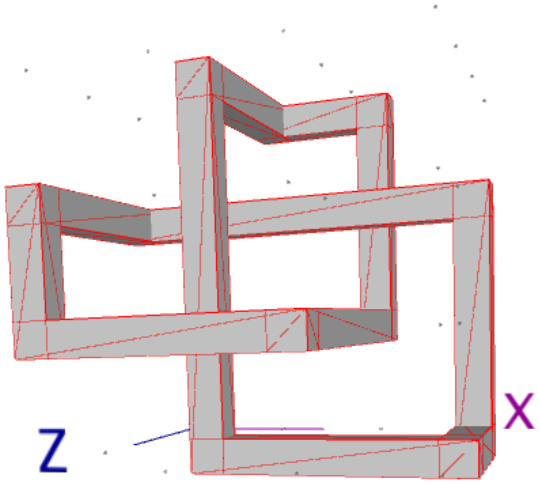

Figure 2.16: A trefoil knot, as modeled on the UCube version of the software. The outlines (strokes) of the knot have been highlighted in red to show the manner in which the software constructs the path; points are expanded into cubes, and adjacent pairs of cubes and then connected with rectangular prisms (the convex hull of two separated cubes).

have a pen on paper, a line will follow wherever you move your hand. The path mode allows for the creation (or close approximation) of most English letters and numbers, common symbols (like stars), and 3D outlines of normally 2D geometric shapes, like triangles and rectangles.

2.4.1.3 Points as "Blocks": Creating Non-Convex Polyhedral Forms

Aside from the convex hull and path operations noted above, the device allows for multiple different semantics for spatial locations. For example, in the path mode previously mentioned, if we choose to construct paths with an edge-length of one "interval unit" of the given device - achieved by putting the software in path mode and setting the "path width" slider to one-half of the distance between points - each cube created will fit perfectly next to its neighbors, turning each point into a sort of "block" . In this way, selecting (say) four successive light locations along the length of one tower, then, one could specify a rectangular prism. Likewise, by selecting three point locations in an "L" form, one could specify the non-convex polyhedral form seen at the far left of Figure 2.17 below.

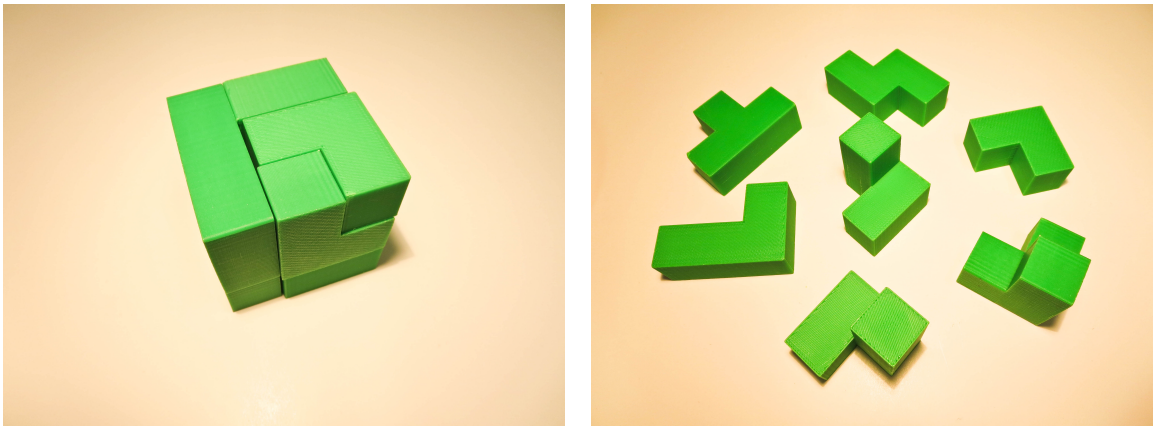

Figure 2.17: A set of non-convex polyhedral forms modeled on the UCube, which constitute the well-known "Soma Cube" puzzle, shown assembled on the left with the individual shapes laid out on the right.

This technique for using the path mode has some interesting advantages in terms of the physical properties of the paths produced in this manner. For those readers interested in recreational mathematics, the shapes shown in Figure 2.17 will be recognizable as the component pieces of the "Soma" puzzle; these pieces can be arranged together to form a larger cube (also shown in 2.17). The software could be employed with any of the devices in similar fashion to produce many such dissection-type puzzles, building blocks, or other for other domains where interlocking, block-like shapes may be useful: architectural mockups, model train environments, real-life Tetris, and a myriad more.

2.4.1.4 Point Clouds: Creating Minimal Spanning Trees

Instead of interpreting points as vertices of a solid (as in the convex hull examples) or as the successive stations of a temporal path (as in the "path" examples above), we could in fact simply treat our set of points as just what they are namely, a set of points. Starting with this interpretation, we might produce a form such as a minimal spanning tree of the set of points (a set of edges of minimal total length connecting all the points). Figure 2.18 shows several examples of forms created this way; one immediately grasps the variance and complexity that this mode is

capable of. The yellow "jack" in the middle of 2.18 is the product of nine points, eight of which form the equidistant vertices of a cube (or what would form a cube if the software were in convex hull mode), with the last point perfectly centered in the middle, effectively "bending" the rest of the graph segments in to meet it.

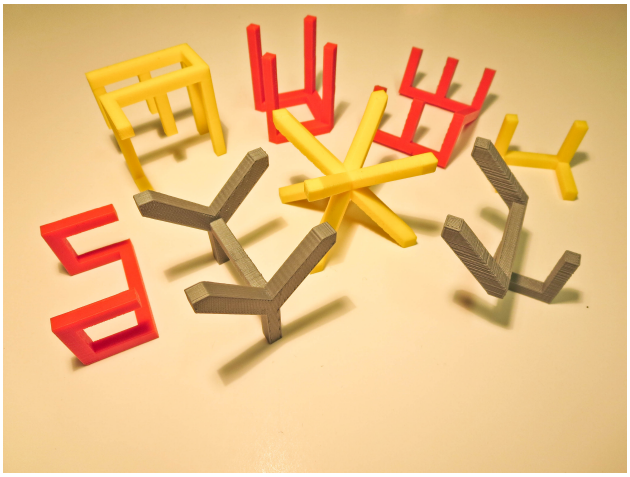

Figure 2.18: Several examples of models produced using the minimal spanning tree mode in our software, exported, and printed out on a 3D printer.

As with the convex hull, the minimum spanning tree is a well-defined, extensively studied algorithm in computer science and mathematics. Given a set of points on a graph, the minimal spanning tree will be a solution (possibly more than one) that connects each point on the graph, without cycles (returning to a point already in the tree), and with the minimal possible value of some "cost" variable, often defined as the sum of "weights" of the connected edges in the tree. One may think of the minimal spanning tree like constructing a subway system, where all the stations need to connect and the length of track should be minimized to keep construction costs as low as possible.

The first algorithm for finding the minimum spanning tree was derived by a Czech scientist, Otakar Borůvka in the late 1920's[27], for the purpose of planning electric distribution networks. There are two popular algorithms used today, Prim's and Kruskal's both of which are considered "greedy" (by iteratively choosing the locally optimal edge to determine the spanning tree) and

run in polynomial time. Our software uses an implementation of Kruskal's algorithm, whereby Euclidean distance between two points on the graph is used as that connecting edge's weight. Kruskal's algorithm, first described in 1956[86], starts by taking a set of each vertex (thought of as separate trees) and a set of all the possible edges in the graph (with their corresponding weights), then iteratively removes the edge with the lowest weight from the set of edges and adds it to the set of vertices, connecting two of these trees into one, until there is only one tree left from the original set of vertices (or we run out of edges to pull from). If there is only one tree left in the vertex set, then that tree represents the minimal spanning tree. It is, of course, possible to have more than one minimal spanning tree for a given graph however.

In our software, we run Kruskal's algorithm whenever a point is added or removed in "tree" mode. The set of points is sent as inputs, the edges and edge distances are calculated, the algorithm is run, and returns a list of connected edges, the set of which is the minimal spanning tree. This list of edges is treated in much the same way as the points in "path" mode: each edge has two point coordinates, both of which are "exploded" into cubes centered on the point, and then the set of two cubes (16 points) are sent to the convex hull algorithm, creating a 3D rectangular prism between the two cubes.

Including the minimal spanning tree mode is an interesting departure from the convex hull and path modes; it is not easily explained to the novice designer, nor does it have the sort of intuitive relationship to the set of active lights as the other modes do. The addition or subtraction of a single point can radically alter the resultant spanning tree in (sometimes) unexpected ways - not so with the convex hull or path modes. However, it is this lack of immediate understanding and the element of unexpectedness that makes this mode a good fit for the kind of devices we make. The real-time adjustments of the software in combination with the exploratory nature of the devices makes the tree mode highly engaging (in our observations, explained in full later on). The ability to quickly add or remove points from the graph is a feature unique to our devices and allows for a quick way to "check and see" different combinations of points and strategies, while being able to look between the device and the software and start to draw some conclusions about

how their actions affect the shapes being displayed.

2.4.2 Other Software Functionality

The software modeling modes mentioned in the last section set the stage for the types of figures that can be constructed with our devices, the software has additional features that are crucial to the overall purpose of the system. This section will go over the operation and methodology of the most important of those: the software's "Edit" mode and the "Export" feature, allowing figures to be saved in a 3D-printer friendly format.

2.4.2.1 Edit Mode

In order to (partially) address the "inflexibility" inherent in having points and thus shapes confined to the integer lattice, we developed a way in the software to "edit" the points by putting the software into a special mode that freezes the serial input from the connected device and allows the user to click-and-drag points off their "hardware defined" locations. The edit mode affects all three of the modeling modes mentioned above, so the user can how the edits they make change each modeling algorithm. We also provide a "reset" button as a way to "snap" back to the original grid of points.

The mode works by combining several pieces of functionality that work together to keep track of the cursor position (to detect if it is hovering over a point) and its click-state, track the relative position of the point as it is being moved, and relay that position information to the data structures responsible for the different modeling modes - all in real time.

Figure 2.19 shows a four-step sequence of screen shots using the edit mode to alter a shape: (upper left) six points have been lighted on the PopCAD and are reflected as simple points in the software; (upper right) the user has selected "tree" mode, taking the minimal spanning tree of the six points, forming a sort of "H" pattern; (lower left) the user selects the "edit mode" button, freezing the serial input and initiating the click-and-drag editing ability; (lower right) the user has dragged each of the four "corner" points outward, altering the original shape into something new,

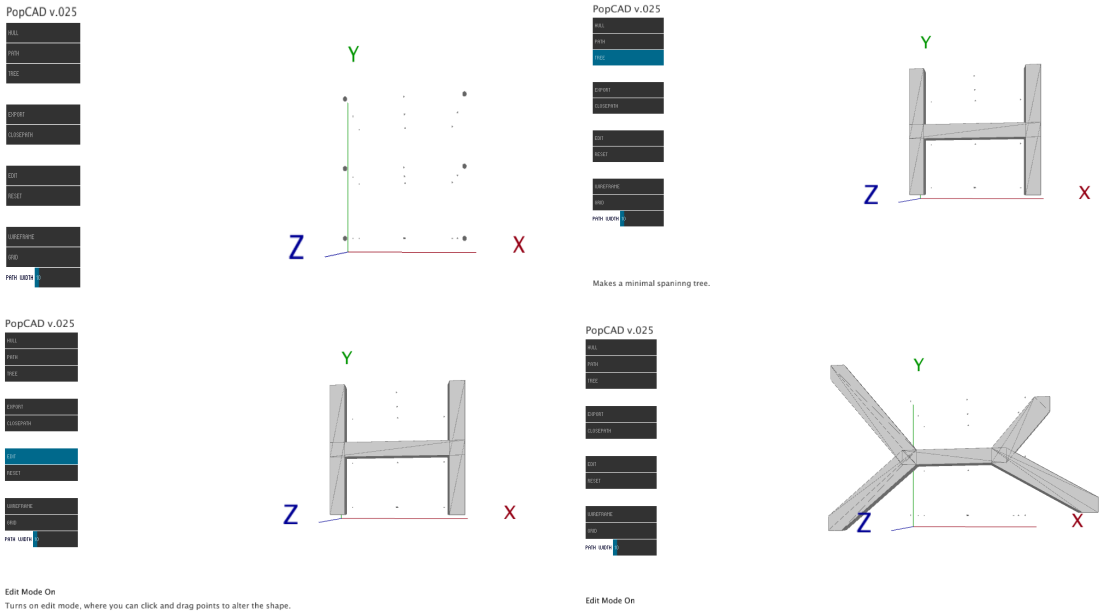

Figure 2.19: A four step sequence showing the operation of the edit mode: (upper left) six unaltered points; (upper right) the points form an "H" shape with tree mode selected; (lower left) the selection of edit mode; (lower right) the edited shape, with the corners of the original shape extended outward.

impossible to model using only the "raw" points available on the device.

2.4.2.2 Stereolithography Export

One of the most important functions of the software is to make a user's creations into easily 3D-printable shapes. Many complex 3D software programs allow for export into sterolithography format (.STL), which is the common input format for 3D printer software programs, however, these programs rarely check to ensure that the produced file will actually be printable; many "model-able" shapes will cause errors in 3D printer software - lines, 2D shapes, shapes within shapes, shapes with gaps between faces - and on and on. Our software also exports into .STL format, but takes great pains to ensure that any exported file will print without error.

The export function in our software deals with models formed from all three modes simply by keeping track of the active mode and choosing the correct export method accordingly. The export process is similar for each type of shape: since each shape is actually constructed of one

or more convex hulls, the array of 3D vectors describing (in order) each triangulated face of the hull (or hulls) is added to a triangle mesh, which takes in all the faces, flips the Y axis values for each coordinate (because in the Processing environment, (0,0) is in the upper left), flips the vertex order, which corrects problems with sliceform errors (in 3D printing software) resulting from the face normal vectors facing the wrong way, then adds all the faces to an .STL object, which outputs a series of triangles in an .STL file the describes the object.

Figure 2.20: Several of the shapes modeled on the PopCAD and SnapCAD devices by novice designers (most of them without any previous 3D modeling expertise) from one of the user studies we performed.

Creating a "novice-proof" stereolithography export (all of the above computation happens with one click, even the file naming) is crucial to the raison d'être of our work - to democratize the process of designing meaningful, personalized objects for 3D printing by novice designers. See Figure 2.20 for a glimpse of what these novice designers are capable of (more to come in later chapters).

Chapter 3

Related Work

The notion of "embodied fabrication" as we have defined it earlier is only cogent given the many philosophical and technological achievements that have helped bring our ideas into being. This chapter is devoted to recounting those accomplishments as they weave through the history of childhood education, developmental psychology, computer science, cognitive science, and digital fabrication to form the foundations upon which our work rests.

The belief that tangible objects[1] play an important role in children's education is relatively recent (given the history of human education). Friedrich Froebel's use of 20 wooden forms he dubbed "gifts" in the first Kindergarten was in 1837[57]. 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[103]. The interest in children's learning methodologies 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[73], including logical-mathematical knowledge related to the kind we wish to foster. Additionally, by using our devices as an assessment vehicle for children's spatial reasoning, one can position our work as part of a tradition (dating back at least to Piaget [112]) in understanding spatial thinking and its development (cf. also [108] for a more recent treatment of the subject). While Piaget's specific theories have been challenged[137][121], his influence was (and

[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.

still is) extremely important. Seymour Papert, one of Piaget's intellectual descendants, published Mindstorms[110] 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 this work derives from an interest not only in constructivist-like activities, but in theories about how interaction with physical objects 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"[149]. 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[38].

Although there are several different tenets of this body-centric view, the primary conclusion relevant to our work is that interactions with physical objects can shape, clarify, and reinforce our cognitive processes in scores of disparate areas. Of keen interest for this work in particular is a domain referred to as embodied mathematics. Lakoff and Nuñez[87] give a fascinating (although not unchallenged - see Voorhees[141] for a good critical discussion) 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[87]. 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. Lakoff and

Nuñez postulate about concepts as ungrounded and seemingly abstract as infinity, although for our work it is enough to suggest that the user interactions present in our designs follow from these four operations and may in fact contribute to the solidification of more complex mathematical ideas in spatial reasoning, 3D modeling, and digital fabrication - for example by forming correct mental models of 3-dimensional objects.

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, again, in Montessori's work (see, e.g., [64]); 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[61], 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". In other work, Ehrlich, Levine and Goldin-Meadow show that through an analysis of hand gestures, one is not only able to predict a subject's "readiness" to learn mathematical concepts[60] but that the kinds of gestures children make (those relating to movement, for example) are correlated with spatial reasoning ability[41] and performance on mental transformation tasks. In fact, we borrow heavily from several of the study designs implemented by Ehrlich and Levine in our own work, especially the last study in Chapter 4 with the PopCAD and SnapCAD devices.

Pedagogical research in embodied mathematics has proceeded hand-in-hand with the development of desktop, embedded, and portable technological artifacts to support the link between bodily actions and mathematical conceptualization. Papert's discussions of the Logo computer language [110] 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.[107] describe the use of a computer-based motion detector system to assist children in the development of intuitions

behind graphing; Howison et al. [68] used a device based on a Nintendo 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.[21] 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 [102] 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.

In their section on 'Thinking Through Doing', Klemmer et al.[83] 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[47]. Resnick's work with "digital manipulatives"[123][153] 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"[76][75] 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 work 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"[123].

Having shown several PopCAD prototypes in Chapter 2 representative of a "renaissance"

in papercrafting by infusing it with electronics, it is worth situating that work in relation to that of other researchers in this (still embryonic) field. The blending of traditional papercrafts with emerging technology is in fact still a relatively novel technique, but there is a remarkable community of researchers beginning to explore this area. For us, a special debt is owed to Leah Buechley's High-Low Technology group at the MIT Media Lab; that group first (to our knowledge) introduced conductive ink and copper tape into paper-based projects. Early (c. 2008) use of conductive ink with microcontrollers on a paper substrate can be found in [35] and [46] with the development of paper-based Arduino processors and simple electronic components (e.g. LEDs, toy motors, switches) that could be placed onto conductive paint to form an electronic connection. This work culminated with a paper application usually reserved for home remodeling: a "living wallpaper"[36] where passers-by could trigger light, movement, and sound by interacting with different parts of the surface (see Figure 3.1).

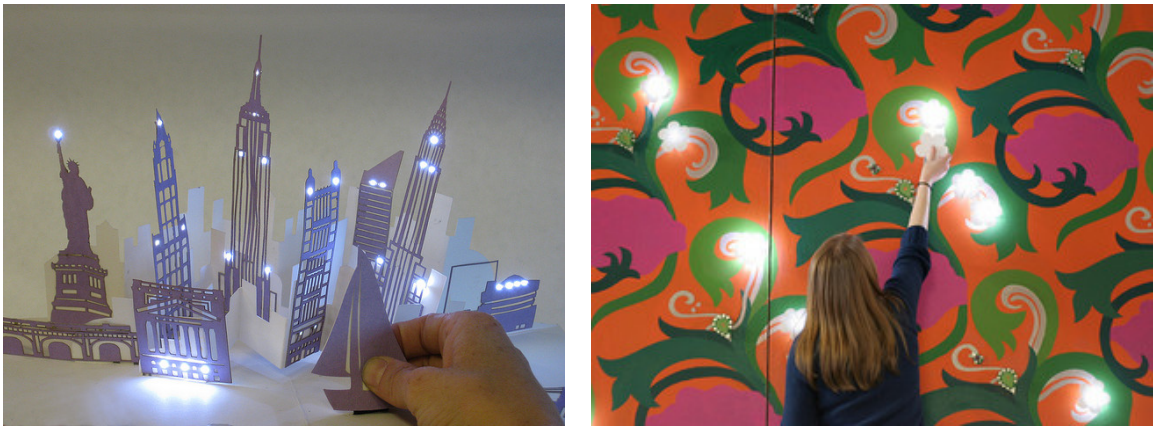

Figure 3.1: Examples of paper-based electronics: Electric Popables (left) is a pop-up book infused with a variety of paper-friendly electronics. The Living Wall (right) is a complete interactive environment embedded in wallpaper, reacting with light, sound, and movement.

These early efforts in turn spawned developments that further refined the expressive potential of paper-based electronics, infusing traditional papercrafts with new elements and abilities. An electronic pop-up book by Qi and Buechley[117] re-imagined the traditional pop-up by infusing each page with paper-friendly, interactive circuitry (e.g. by using a copper tape circuit to

power LEDs in a pop-up cityscape), and from which PopCAD certainly owes some debt. Other projects in this vein include techniques to animate origami structures through shape-memory alloy (SMA)[118], using SMAs in the design and fabrication of printable paper-based devices (e.g. speakers and lamps)[127], storytelling and craft-making through electronically-enhanced storybooks and workshops [77][37][139] and the use of small microcontrollers incorporated into programmable paper-based sculptures[100].

These efforts have focused on the creation of compelling (either electronically or digitally enhanced) papercrafts. There are numerous technological developments that, in combination, serve to accelerate the development of paper mechatronics. For instance, Kawahara et al.[82] describe how inkjet-ready conductive ink can allow circuits to be printed easily and directly onto paper; and Koizumi et al.[84] present a toolkit for wireless control of movable paper toys, Zhu et al.[151] describe a method for wireless power transfer for paper computing, and Coelho et al.[39] have achieved the direct embedding of conductive components during the papermaking process.

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[48], a construction kit with kinetic memory so as to record and playback certain user-generated manipulations[120], as well as several variations of "smart-cube" interfaces [143][129] 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[26], arguing for a kindergarten-influenced approach to creative thinking[122], embodied approaches to analyzing children's interactions with smart objects[15], as well as the embodied design of interfaces for introducing mathematical concepts to kids[11] have shown a great degree of correlation between physical interaction and learning in children.

Figure 3.2: Left: The ActiveCube system. Right: The Roblocks system.

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[55], 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[70] 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"[148]; 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)[106], 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[152]. These projects, as well as several others that deal specifically with digital fabrication for laser cutting[78][147], 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 do they cover the range of possibilities for child-friendly input devices that focus on 3D-printing.

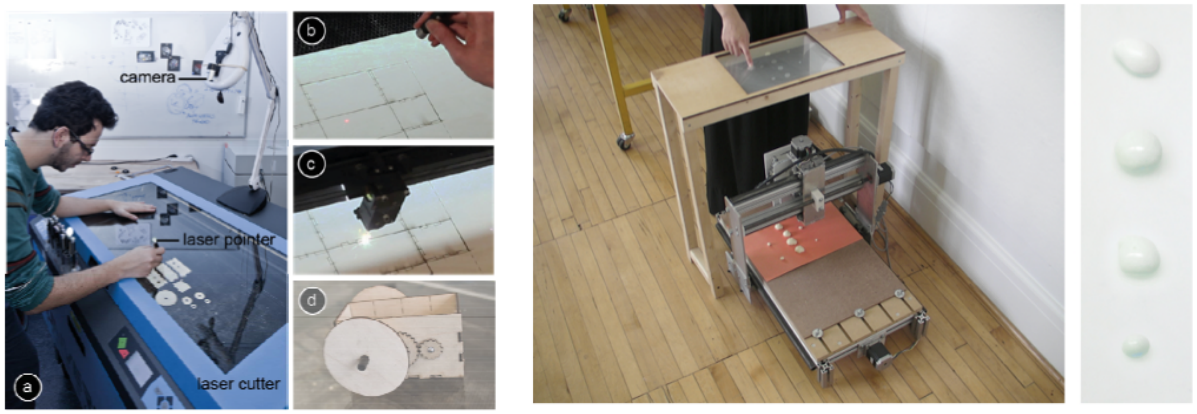

Figure 3.3: Examples of interactive fabrication interfaces: Constructable (left) allows users to control a laser cutter with a set of physical tools as opposed to a pre-defined design file. Shaper (right), and interactive fabrication tool using expanding polyurethane foam.

Therefore we argue that there is room for novice-oriented designs such as the devices described in this thesis, as well as a pre-existing lineage that suggests meaningful results may follow from continuing to explore the incorporation of tangible interfaces with embodied design.

We see our devices as part of a larger, burgeoning "technological ecosystem" around the democratization of three-dimensional printing (and new fabrication technologies more generally). The introduction chapter to this work noted several prominent researchers who argue for democratization of these technologies, and for its applications to education. Indeed, exciting early work has been done in applying 3D printing to education in fields such as architecture [29], solid geometry [66], and mechanical design [93]. Our devices are designed so that they can be employed by younger students our studies focused primarily on middle-school aged children (11-14) - who are certainly less skilled or experienced with traditional 3D modeling software than the average engineer or architecture student. The devices we present are meant 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, they are not simply devices for mathematical instruction, nor even a general tool for mathematical design - but as a suite of experiential, embodied interfaces for engaging youth in a variety of spatial design activities

Figure 3.4: 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.

aimed not only at learning but at democratizing authorship for 3D printing as well.

Chapter 4

Evaluation

This chapter is devoted to the description and discussion of three separate user studies with the devices introduced in Chapter 2. Two studies were performed with the original UCube device (one more informal than the other), while a longer, more detailed study involved both the SnapCAD and PopCAD systems. We present the procedure, results, and basic observations of each study in this chapter, and discuss the results more thoroughly in the next chapter.

4.1 UCube Pilot

Early in 2011, shortly after the UCube prototype was complete, we conducted an initial (and informal) pilot study with the UCube. Our participants were a group of 12-14 year old middle school children from a local middle school multimedia class. We had fourteen participants (predominantly Caucasian), consisting of five girls and nine boys, who were divided into six groups (five groups of two, one group of four).

4.1.1 Procedure

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 4.1). 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.

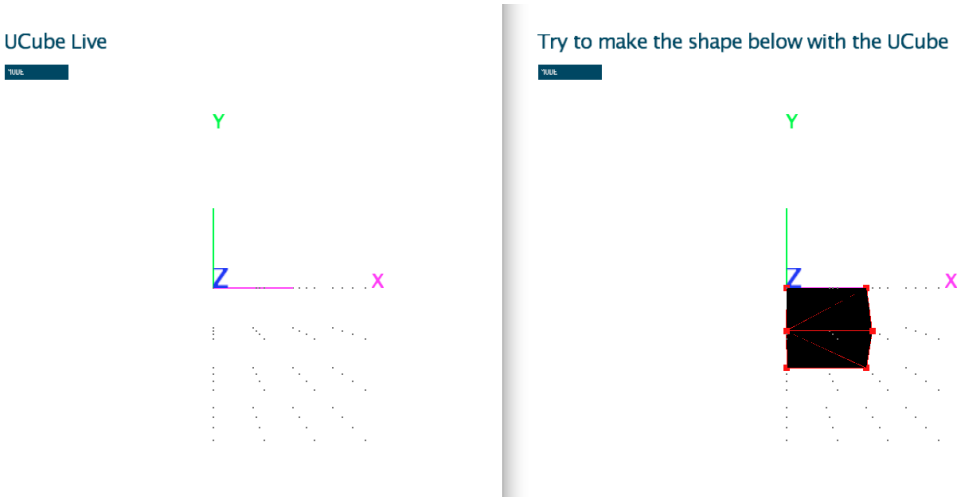

Figure 4.1: A screenshot of the testing setup, with the live output from the UCube on the right and the target shape on the left.

Participants were instructed to place the tower 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".

4.1.2 Results and Observations

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, for a total of 24 of 30 possible shapes, or 80%. 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 a small, informal study on its own, 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. 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, prompting refinement of the UCube software and hardware as well as further user study, as we explain below.

4.2 Further UCube Study

Early in 2012, we conducted an IRB approved follow-up 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. Each participant was individually led through two separate exercises (outlined below) using the UCube.

4.2.1 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.

4.2.2 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 4.2 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.

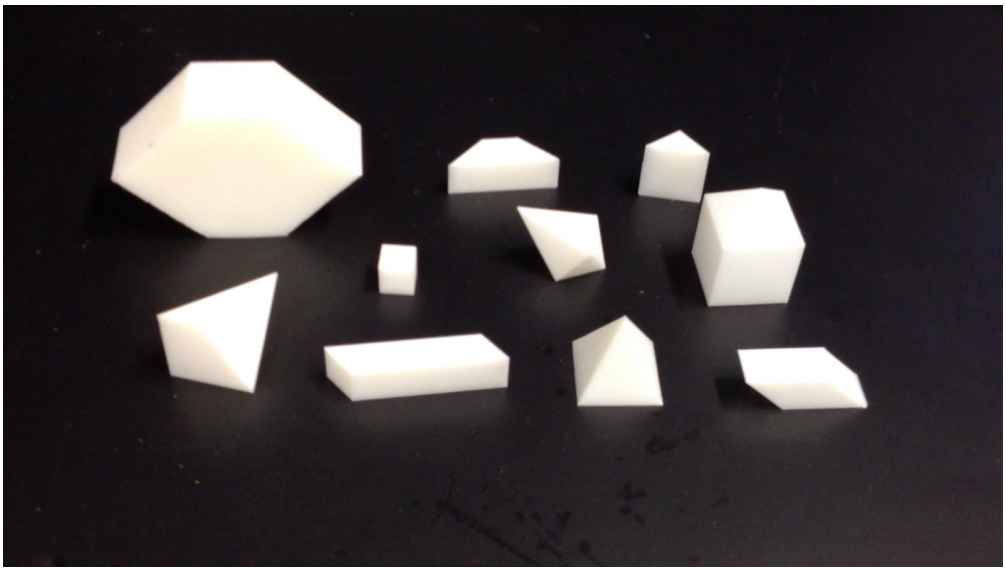

Figure 4.2: The nine models used during the user study: a diamond, trapezoid, parallelogram, cube, elongated hexagon, irregular polyhedron, triangular prism, tetrahedron, house.

4.2.3 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.

4.2.3.1 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 ten participants, eight were able to recreate the cube from memory, whereas only four 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 three of the ten participants either after continued possession of the shape or using the software.

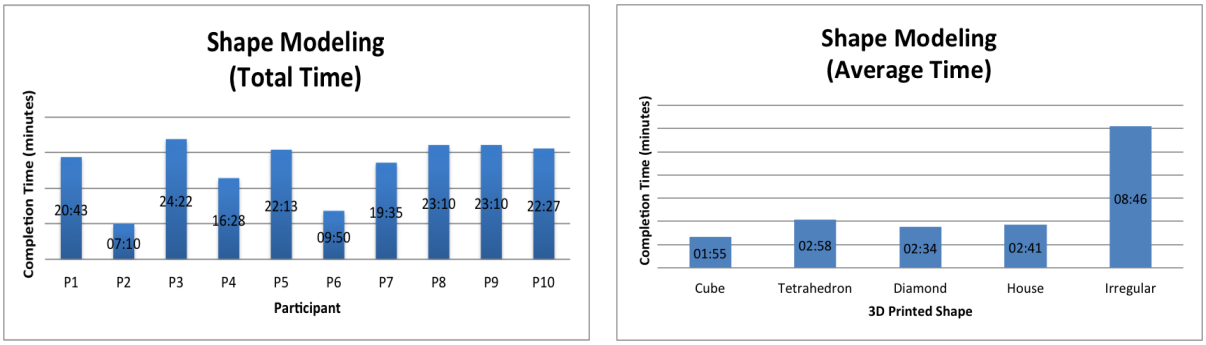

Figure 4.3: Results of the modeling task, showing total modeling time spent per participant (left) and average modeling time spent per shape across participants (right).

The graphs in Figure 4.3 represent 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.

4.2.3.2 Exercise 2: Matching

Out of 50 matching tasks (five per participant), all but three tasks were completed in 20 seconds or less. Figure 4.4 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.

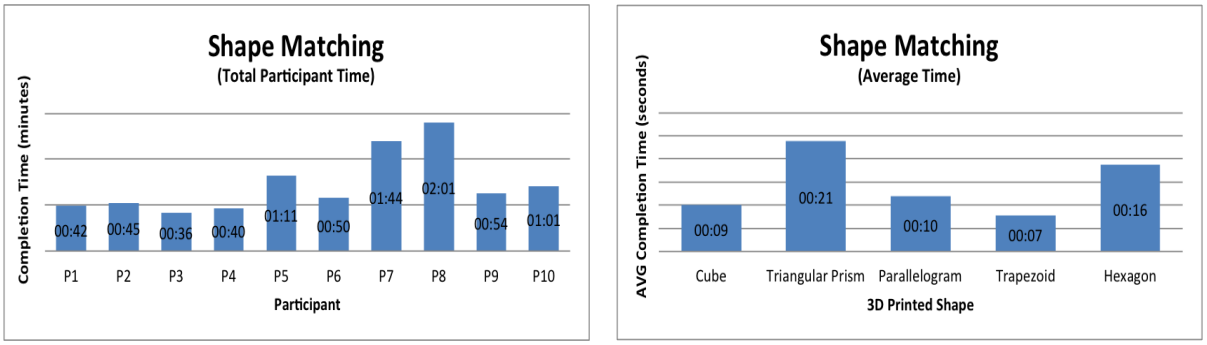

Figure 4.4: Results of the matching task, showing total time spent per participant (left) and average time spent per shape across participants (right).

4.2.4 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).

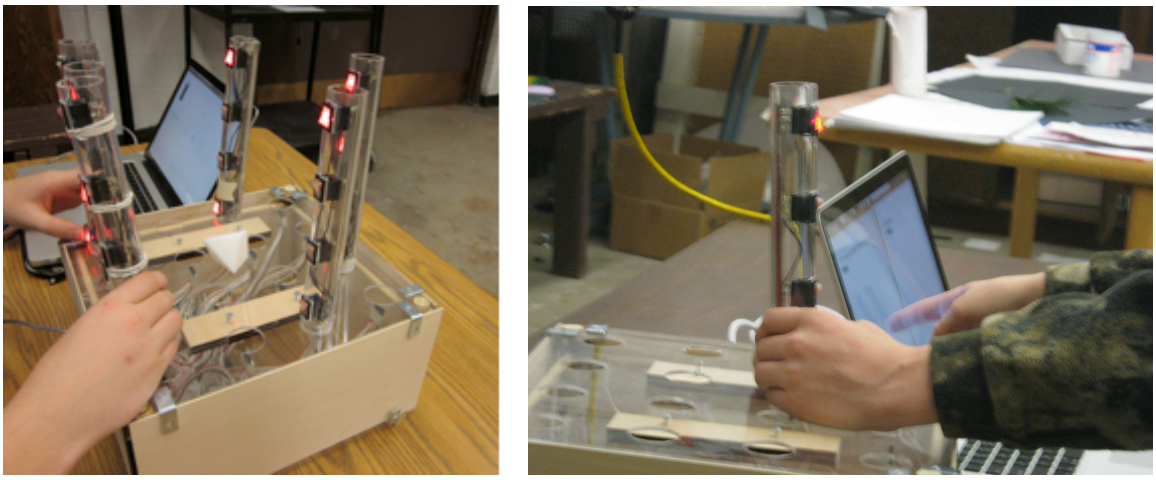

Figure 4.5: Left: A participant using a strategy of placing the physical model on top of the UCube while using both hands simultaneously to manipulate the towers. Right: A user pointing at the software representation of the shape with one hand, while manipulating the UCube interface with the other hand.

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 4.5 for an example). These gestural and "embodied" interactions with the UCube, combined with a high degree of modeling success spurred us not only to create a more robust and expressive system (called - SnapCAD - as detailed in Chapter 2), but to attempt to tease out the relationships between modeling on these kinds of devices and the gestures and speech produced when subjects were explaining their strategy in using the devices. This eventually led to a comparative study using two new devices, two new modeling modes, and introducing metrics to analyze some of the "embodied" aspects hinted at above.

4.3 SnapCAD and PopCAD

Starting in early 2014 we conducted a study using both the SnapCAD and PopCAD devices with a group of 11-18 year olds at a local drop-in enrichment program that focuses on children from under-served and low socioeconomic communities. Twenty participants enrolled in the study, consisting of 12 boys and 8 girls (no one responded with other, although it was an option). We collected some basic demographic information, including age, race, grade level, 3D modeling experience, 3D printing experience, computer ownership and use, interest in engineering, and how

difficult they thought classes in school were. Parental consent was obtained (and child assent given) for each subject in the study.

To present a snapshot of the demographic findings, then: the participants were primarily of Latino or Hispanic descent, but also included those of African-American, American-Indian, Asian, and Caucasian descent. Grade levels ranged from 6th-12th, with an overall average of 7.9 (8.33 for boys, 7.75 for the girls). Average age was 14 years, 1 month, 20 days (14 years, 6 months for boys, 13 years, 7 months for girls). 18 of 20 participants had a computer at home. Describing their comfort level using a computer on a scale from 1 to 10 (10 being most comfortable), the participants averaged 7.9 (8 for boys, 7.75 for girls), with no scores below a 5. Of the participants who had a computer at home (all but two of the subjects), two reported using it only a few times a year, five used it a few times per month, four used it a few times per week, and five reported using the computer everyday. Only three of the participants had any experience with 3D modeling software. Interestingly, only two of the participants had never heard of 3D printing before enrolling in the study, but none of them had ever designed or printed anything using a 3D printer - further underscoring the lack of available tools for novice designers. When asked about their interest in engineering, only seven children (all boys) stated they were definitely interested. However, only two children (both girls) stated that they were definitely not. The rest (11 kids) stated that they were either "maybe" interested, or "not sure". When asked how difficult they felt school classes were, six responded "easy for me", 10 said 'somewhat easy for me', and four responded "somewhat hard for me" (no one responded "hard for me").

4.3.1 Procedure

The study ran for seven weeks total, comprising several stages, the first being a pre-assessment of spatial reasoning skills. The spatial reasoning assessment was done using the "Children's Mental Transformation Task" developed by Susan Levine ([41] pp.1260-1261). In the task, participants are shown two pieces of paper, side-by-side. One piece shows a 2D geometric shape, split apart and rotated in one of several different ways. All shapes were symmetrical either horizontally or

vertically (or both), and thus split along either a vertical or horizontal line of symmetry. Shapes were translated in one of four different ways: (a) translated perpendicular to the line of symmetry (direct translation), (b) translated and then moved diagonally apart (diagonal translation), (c) rotated 45 degrees outward from the line of symmetry (direct rotation), or (d) rotated and then moved diagonally apart (diagonal rotation). The other piece of paper contained the geometric shape, recombined correctly, along with three incorrect choices. In the study we conducted, participants were given two sets of 10 shapes, one set as a pre-assessment before doing any modeling, and another (completely different) set of 10 after completing the entire study, as a post-assessment. Figure 4.6 shows an example instrument, with the four possible translations.

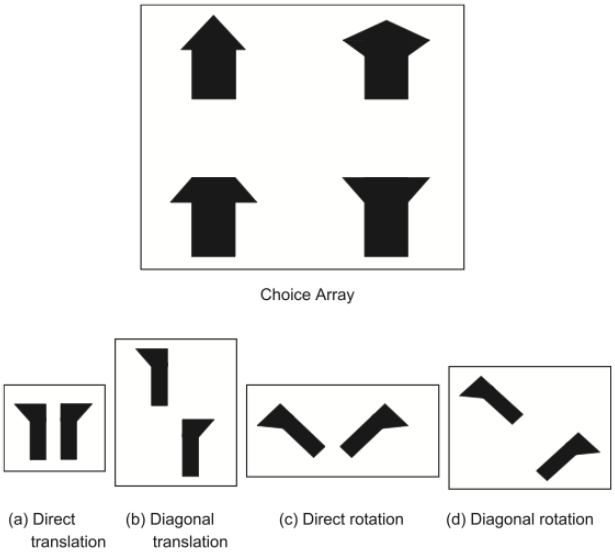

Figure 4.6: An example problem from the spatial reasoning exercise. The figure at the top shows the choice array of four shapes, where the lower right figure is the correct option. Examples (a) through (d) show the four different types of translations found in the exercises - direct translation, diagonal translation, direct rotation, and diagonal rotation.

After the pre-assessment, participants were split into two groups of 10 students each - the selection alternated evenly based solely on order of participation - with group A modeling first on the PopCAD and group B modeling first on the SnapCAD (each device is described in Chapter 2). Each session begins with a brief ($\approx$ one minute) introduction to the device, during which the

participant is told how to operate the device, but not what any of the software buttons do, and given free time to become comfortable with the interface. Participants were encouraged to explore both the interface, and the buttons in the software that control the three primary modeling modes (convex hull, path, minimal spanning tree).

Once the subject indicates that they are ready to move on (capped at 10 minutes), we move into a series of three modeling exercises that explore each of the aforementioned modes. The basic operation and a brief explanation of each mode were given to the participants as an introduction to each mode. Four 3D-printed models representative of each mode were presented to the user in an order judged to be from least complex to most complex (and thus was the same for each user), for a total of 12 modeling tasks across the three modes. 24 models were used - one set of 12 was used across every user's first session (independent of device), with a remaining 12 models used in every user's second session. Figure 4.7 shows the two sets of models side-by-side.

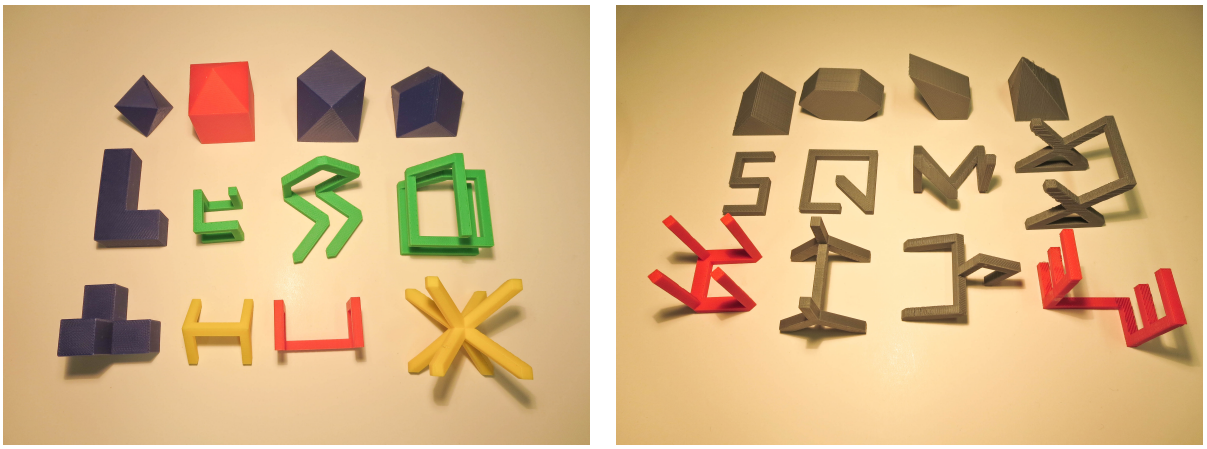

Figure 4.7: The two groups of 12 3D printed models used in the first session (left) and second session (right). Each row is a different modeling mode (back = convex hull, middle = path, and front = minimal spanning tree). The shapes were presented in order from left to right as pictured above.

The tasks that follow are the same for each device:

Tasks 1-3: Convex Hull Modeling, Path Modeling, Minimal Spanning Tree Modeling

Before each set of modeling tasks, the participant was given a brief demo of how each modeling

mode interprets the points from the device. The user was then presented with a series of four (4) plastic, 3D-printed models that were modeled on the device using the current modeling mode. For each of these shapes, the participant attempted to recreate the shape using the modeling abilities of the device and the software. The user was be instructed to indicate when they believe they have successfully recreated the shape, as well as to think aloud about their modeling process. The time to completion (of lack thereof), completion code, observational notes, and video were recorded. If the user indicates modeling success, they shall be asked to explain their modeling strategy for the purpose of logging gesture and speech data.

Task 4: Freehand Modeling

After the modeling tasks are complete, participants were invited to "freestyle" model an object of their choosing, using any of the three modeling modes. By asking participants to think aloud about their intentions and thinking processes during this exercise, we aimed to gain a deeper understanding of the strengths and weaknesses of the system, as well as the thought processes and engagement of the users in attempting to model a specific model of their own choosing. These saved models were analyzed, based on which mode was used to create them, complexity (based on number of points, faces, segments, and symmetry), and whether the shape was "exploratory" or "intentional" (i.e. was the end artifact a result of sort of happy accident, or the result of intentional process to create a specific model).

For the first three modeling tasks (but not the freestyle modeling), time to completion (or request to move on) was recorded, along with an outcome code. The outcome was coded according to a set of conditions detailed below in table 4.1, and was developed upon analysis of the recorded video, in an attempt to fit the sorts of repeated behaviors that were in fact observed.

Participants were asked to "think aloud" about their process, difficulties, modeling choices, etc. In the case that the user believed they had correctly modeled the shape (cases C and E2 in table 4.1) they were asked to explain their modeling strategy.[1] Their explanation was videotaped and

[1] Cases E1,E3,E4, and I did not provide the grounds from which to ask about modeling strategy and so were not recorded.

Table 4.1: The coding used in analyzing the modeling exercise outcomes, based on observations from video taken during the study.

Category	*Code*	*Definition*
Correct	C	A complete and correct modeling of the shape
Error in recognition	E1	The correct shape was modeled, but the user did not identify it
Error in belief	E2	A belief that the modeled shape has been modeled correctly, when it has not
Error in implementation	E3	User knew shape was incorrect, and gave a correct explanation
Error in strategy	E4	Knew shape was incorrect, and did not know why or gave an incorrect explanation as to why
Error in proportion	EP	The general shape is correct, but the proportions in one or more dimensions is off (e.g. too tall, not wide enough, etc.)
Incomplete	I	Participant ran out of time, gave up, or asked to move on

analyzed based on the coding strategies laid out in "The Importance of Gesture in Children's Spatial Reasoning"([41], p.1264), laid out in table B.1 below. The rationale for performing this analysis in based in part on work by Ehrlich, Levine, and Goldin-Meadow [41][91][61], which suggests that the frequency of gesture and relationships between speech and gesture act as a window into the learning state and performance of the subjects.

The second session was similar to the first, with the subject using the device not used in session one (no subject used the same device twice), and with 12 new models. Once modeling on the second device was completed, users took a second spatial reasoning assessment of an additional ten questions to help gauge if any meaningful difference in spatial reasoning skills has occurred throughout the study.

A slightly modified version of the software was used for the user study, eliminating several of the functions not being evaluated for the sake of presenting a clear interface for the users. The multiple hull modes, spline, load, and save functions (described in Chapter 2) were eliminated, and the rest of the graphical user interface was reorganized and streamlined. We combined the three different .STL export buttons into a single export button that handled all three modes, changed

Table 4.2: The various coding strategies used in the video analysis of subjects' modeling strategy explanations. Borrowed and adapted from [41].

Category	*Definition*	*Speech Examples*	*Gesture Examples*
Movement	Any indication of movement	"Just slide them together and then it looks like that"	Miming movement with the hands
Perceptual Features	Focus on a particular feature of the model	"Because there is a little bend in here and a point thing here"	Pointing to a specific feature on the model
Perceptual Whole	Any indication of seeing the model as a whole	"It looks like an arrow!"	Gesture indicating inclusion of the whole shape
Vague	An expression of strategy that the coder cannot decipher	"Because I looked at that and I looked at the differences"	Waving gestures above the computer device that do not indicate any specific strategy
Other	Any strategy not listed above	"And here is like half of it. But so and two halves make a whole"	Using the hand to form a straight line through the middle of the whole shape to represent the line of symmetry

the order of the remaining buttons and made them larger, and made the X,Y, and Z axis markings larger.

4.3.2 Results

This section reports on the results from our study, relaying our findings across both sessions, genders, modeling modes, and spatial reasoning scores in an attempt to tease out what conclusions, if any, we might make about the strengths and weaknesses of our devices as well as how interacting with our devices affected user's spatial reasoning abilities, 3D modeling skills, or congruence between speech and gesture in explaining the cognitive learning state of the user.

4.3.2.1 Modeling Results

In this section we will focus on delivering the results from the modeling exercises. Users went through two sessions, modeling 12 shapes each time (four shapes each using convex hull, path, and minimal spanning tree modes) for a total of 24 exercises. For each modeling task, a result code was

recorded per the rubric shown in table 4.1. One user dropped out of the study (user six) before completing round one, leaving us to report on 19 users for the first modeling session, ten of whom started on the PopCAD and nine of whom started with the SnapCAD. A further three users did not complete session two, leaving 16 users, seven girls and nine boys, who were split evenly over the two devices in the second session (eight each on PopCAD and SnapCAD).

Table 4.3: An overview of the modeling task results, broken down into session number, gender, device, and modeling mode.

	Session 1	%	*Session* 2	%	*Total*	%
Overall Correct	127/228	55.7%	116/192	60.4%	243/420	57.9%
Girls	45/84	53.6%	55/84	65.5%	100/168	59.5%
Boys	82/144	57.6%	61/108	56.5%	143/252	56.7%
PopCAD	90/120	75%	62/96	64.6%	152/216	70.4%
SnapCAD	37/108	34.3%	54/96	56.3%	91/204	44.6%
Convex Hull	40/76	52.6%	38/64	59.3%	78/140	55.7%
Path	48/76	63.2%	44/64	68.8%	92/140	65.7%
Tree	39/76	51.3%	34/64	53.1%	73/140	52.1%

Out of the 228 modeling tasks in session one, the group successfully modeled 127, or roughly 56%. Those users who started with SnapCAD performed 37 of 108 tasks, or 34%, while those using the PopCAD device completed 90 of 120 tasks correctly, for a success rate of 75%. Girls completed 45 of 84 tasks (54%), while boys correctly completed 82 of 144 tasks (58%). Individual scores ranged from 0 to 12 (perfect), with an overall overage of 6.68 correct shapes per user. Average correct shapes per user was 4.11 for SnapCAD and 9.00 for PopCAD.

In session two, 116 of 192 (60%) tasks were performed correctly, with SnapCAD modelers correctly representing 54 of 96 shapes (56%) and PopCAD modelers completing 62 of 96 shapes, or roughly 65%. Girls completed 55 of 84 tasks (65%) while boys completed 61 of 108 tasks for 56%. Individual scores ranged from 3 to 12 (perfect), with an average of 7.25 correct shapes overall, while the average correct shapes per user was 6.75 for SnapCAD and 7.75 for PopCAD.

The two bar graphs in 4.8 show the average modeling times broken out over device and gender

(on the top) and modeling mode (on the bottom). Modeling times were recorded from the time the user was handed the shape until they indicated either that (a) they believed the model to be complete, or (b) they gave up, wished to move on, or thought they were as close as they were going to get (though they knew their model to be incorrect).

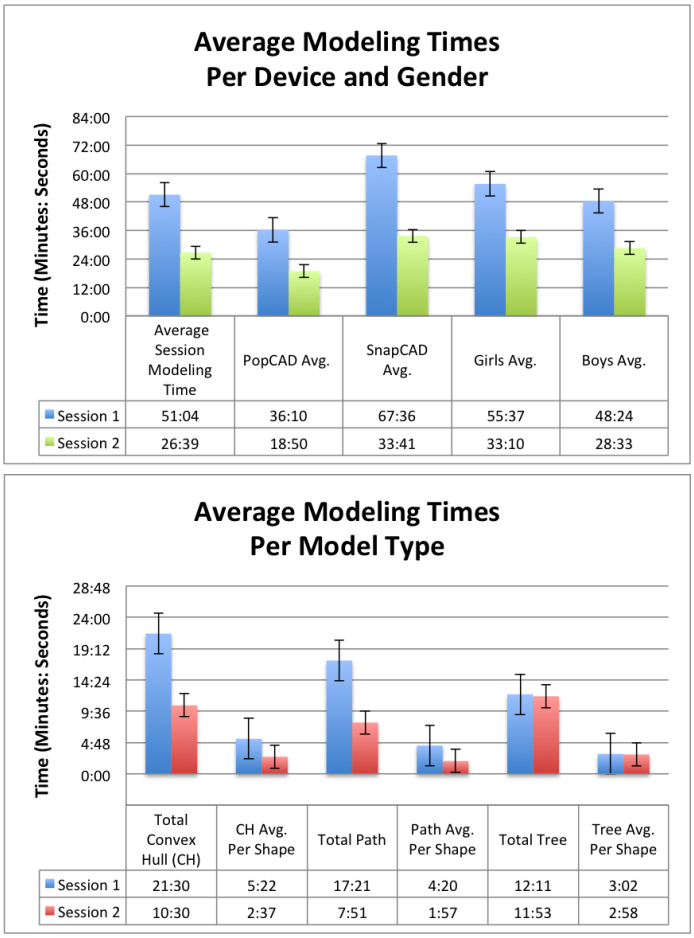

Figure 4.8: The average recorded modeling times for each session, broken out (on top) by device and gender, and (on the bottom) by modeling mode. Error bars show standard error (SE).

We can easily pick out a few trends from these two graphs: average modeling session time went down significantly in the second session, regardless of device or gender, although boys took less time in both sessions, and the PopCAD seemed to take less time overall in each session than modeling on the SnapCAD (although interestingly, the SnapCAD modelers in the second round improved on their times from modeling on the PopCAD in the first round). When examining mode

types, we see a similar trend of significantly decreasing modeling times in the convex hull and path modes, but curiously, not in the tree mode where times improved in the second session by only a few seconds. While the minimal spanning tree mode took subjects the least amount of time (of the three modes) in session one, the improvement in both convex hull and path modeling times left the spanning tree with slowest overall and average modeling times in session two. Seeing as the minimal spanning tree mode posted the lowest percentage of correct shapes in both rounds (and thus overall), we might expect the ranking we observed in round two, where average modeling times corresponded with the overall percentage of correct shapes. It seems plausible that mastery of the tree mode is slower to arrive than either the convex hull or path modes, and therefore one extra session produced more dramatic results in the other modes (convex hull and path modeling both improved by almost 7% in session two, minimal spanning tree by less than 2%).

4.3.2.2 Mental Transformation Task Results

Subjects were given two sets of 10 mental transformation problems, as discussed previously in the procedure section. The first set was given before the first modeling session, as a sort of pre-assessment. The second set was given after the second modeling session as a post-test. We recorded performance data by session and by user, and present the results in Figure 4.9 broken out by the type of symmetry represented in the shape (unilateral or bilateral) and the type of translation or rotation performed on the shape (direct or diagonal translation, direction or diagonal rotation), meaning that each shape had both a symmetry type and a translation type.

Overall, subjects performed very well on the Mental Transformation Task, correctly responding to 614 of 720 questions (a little over 85%). Performance was remarkably equal across genders, with girls correct on 256 of 300 (85.3%) and boys on 358 of 420 (85.2%). Accordingly, we found no sigificant difference in gendered responses across any symmetry or translation type - girls and boys succeeded and struggled on the same sorts of tasks. Bilateral symmetry was significantly easier than unilateral, with over 90% of bilateral tasks and only 78% of unilateral tasks performed correctly. Rotation was more difficult than translation, and diagonal transformations were more

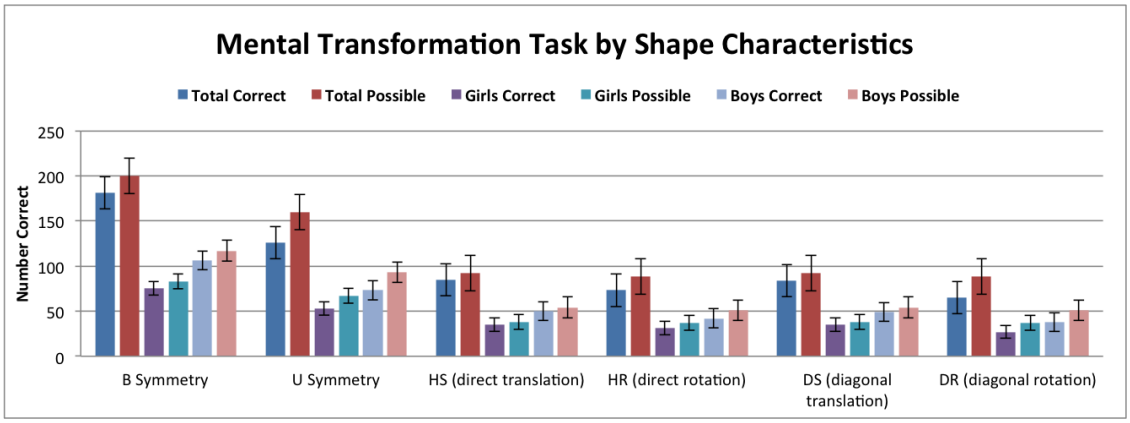

Figure 4.9: A view of the Mental Transformation Task results, broken out by symmetry type (B = bilateral, U = unilateral) and rotation or translation type performed on the shape being transformed.

problematic than direct ones. Hence, diagonal rotations scored the lowest (75%), followed by direct rotations (82%), diagonal translations (91%), and direct translations (93%).

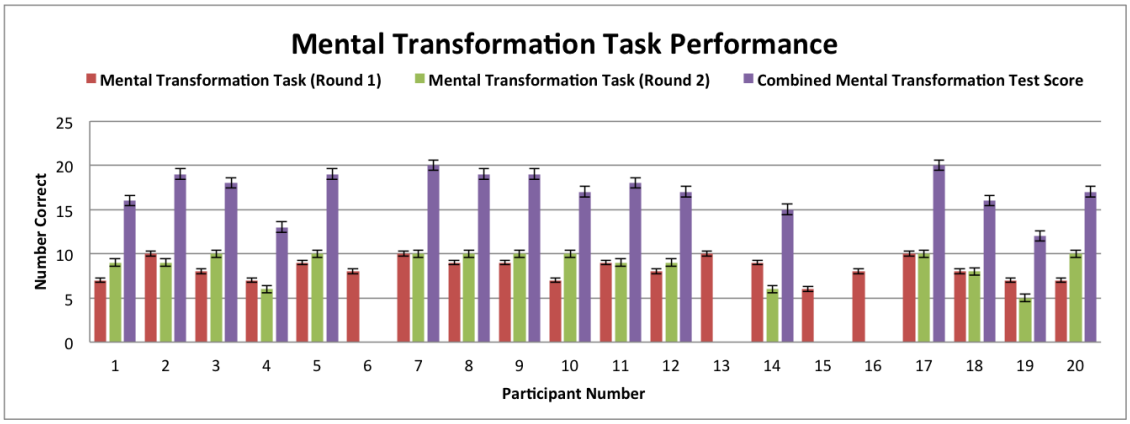

Figure 4.10: Mental Transformation Task results, broken down by session and by user.

Figure 4.10 shows the Mental Transformation Task results broken down into sessions by user. We observed a +7 net improvement in the second round among the 16 users who participated in both sessions. Both girls and boys improved in the second session, though girls improved by a greater percentage when compared to boys - from 82.3% to 88.6% while boys improved from 83.3% to 87.7%, a 2% greater improvement among girls. Four users did worse on the second set of tasks,

four did the same, and eight improved; the greatest change in both directions was +/- 3. There was a no real correlation between improvement between sessions (or lack thereof) and modeling performance overall ($r = .20$, $p < .5$), nor was there a real correlation between improvement on the Mental Transformation Task and improvement in modeling score from session 1 to session 2 ($r = -.20$, $p < .5$), suggesting that the **change** between sessions on the spatial reasoning test and modeling performance are mildly related, if at all.

4.3.2.3 Speech and Gesture Coding Results

During the modeling exercises, if a subject believed (correctly or not) that they had successfully modeled a shape, the facilitator asked the subject to describe the modeling strategy they used to arrive at their answer. During these explanations, video recordings were analyzed for five types of speech and gesture behaviors: those referring to movement, to the perceptual whole of the shape being modeled, to a perceptual feature of the shape being model, as well as behaviors that were vague or unintelligible, and those that did not fit into any of the above categories (labeled as "other" - a more detailed description is available in the procedure section above). A given strategy was only recorded once per modeling task, but multiple strategies per explanation occurred often and were recorded (as was also the case in [41]). The table below breaks down the numbers and types of speech and gesture observed over the two sessions; as such, we only report on the 16 subjects who completed both sessions. For further insight into how some of the modeling strategies were expressed by the users as well as the associated coding and gesture observations, we have compiled a set of excerpts in Appendix B. These excerpts contain quotes from users while explaining their modeling strategy, the observed gestures that occurred during the spoken explanation, and the speech and gesture codes generated from those expressions.

Table 4.4 shows the total number of gesture and speech types we recorded, as well as how they were split between each devices, genders, and sessions. The most common gesture and speech types (by a significant margin) were about specific perceptual features of the models, those relating to movement came next, followed closely by vague gestures and speech. The other two categories,

Table 4.4: Gesture and Speech Observations over both sessions. Numbers in this table exclude the totals from the three subjects who finished the first session but not the second.
G = Gesture, S = Speech, .M = Movement, .PW = Perceptual Whole, .PF = Perceptual Feature, .V = Vague, .O = Other.

	Total		*PopCAD*	*SnapCAD*		*Girls*	*Boys*		*Session* 1	*Session* 2
G.M	113		62	51		73	40		39	74
G.PW	13		8	5		8	5		9	4
G.PF	180		102	78		96	84		93	87
G.V	100		50	50		42	58		34	66
G.O	7		4	3		6	1		4	3
S.M	107		64	43		55	52		46	61
S.PW	68		39	29		35	33		38	30
S.PF	186		103	83		97	89		101	85
S.V	104		55	49		40	64		32	72
S.O	70		35	35		33	37		18	52
Gesture	413		226	187		225	188		179	234
Speech	535		296	239		260	275		235	300
Combined	948		522	426		485	463		414	534

perceptual whole and "other" strategies, were barely represented in gesture - they were far more common in speech, but still ranked as the least frequently recorded. Many users explained their modeling strategy by doing a "step-by-step" recounting of their process that referred at each step to the part of the shape they were modeling at that point. For example, it was common for a subject to point to a segment of the model and say (for instance), "and then I put a point here, for this part…", generating perceptual feature scores in both gesture and speech for nearly every explanation they gave. Movement was often explained along the same lines (though less frequently), often with subject using specific words that indicate motion (e.g. "then I move over here", "I had to go up here, then follow the path back down again") while simultaneously motioning along the directions they were indicating. Figure 4.11 shows a series of six still shots taken from the video that depict (as best as possible in a single frame) various gestures made during a single explanation of a modeling task strategy.

Interestingly, even without accounting for the difference in number of subjects, girls "out-

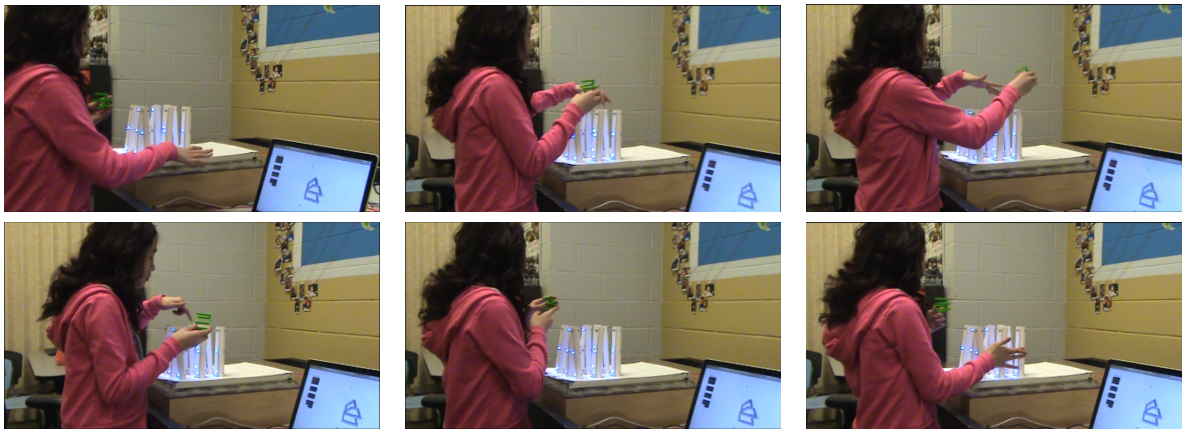

Figure 4.11: A series of screen grabs from the video recording showing various gestures from a user explaining her modeling strategy on one of the modeling tasks.

gestured" the boys overall (225 to 188), and in every category **except** for vague gestures, where boys were vague in describing their strategies 24 more times over the course of the study. Speech types were more gender-balanced, with the final tally being 260 for girls and 275 for boys, however seeing as boys had more participants in both sessions of the study, the speech-per-participant count actually favors the girls as well. The PopCAD interface produced more gestures (226 to 187) and speech (296 to 239) than the SnapCAD, a finding mitigated somewhat by the fact that users modeled so poorly on the SnapCAD in the first round and therefore did not arrive at a point where a modeling strategy could be explained. If we isolate the second round only, where the performance breakdown was much more even (62 to 54 in favor of PopCAD), then SnapCAD actually produced more gestures (124 to 110) and more speech elements (159 to 141).

Perhaps the most curious data from Table 4.4 is the big increase in both gesture and speech from round one to round two of the study. Even with three less participants in round two, overall instances of gestures increased from round one by 55 (179 to 234, a 31% increase), and speech instances increased by 65 (235 to 300, a 28% increase), yet the overall modeling performance only increased by 5% in round two. A bit of a closer look at the types of gesture and speech gives a plausible explanation: in both gesture and speech, the number of **vague** indications rose dramatically (+32 for gesture, +40 for speech), while the number of perceptual feature indications

dropped in both cases (-6 for gesture, -16 for speech). If we look at Figures 4.12 and 4.13 these numbers start to make more sense.

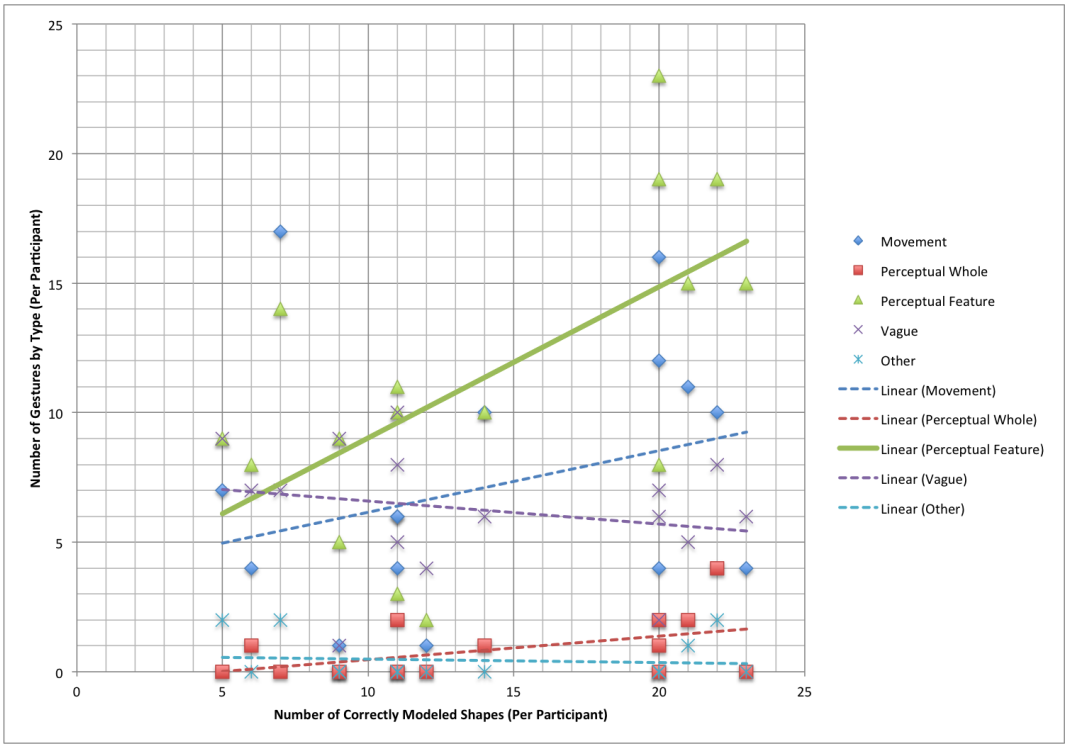

Figure 4.12: A plot of the five types of gestures we coded (movement, perceptual whole, perceptual feature, vague, and other) over the number of correctly modeled shapes. The slope of the lines indicate the strength of correlation between each gesture type and overall modeling performance.

Figure 4.12 shows a plot of the number and kind of gestures produced by a user over the number of shapes they modeled correctly over the two rounds of the study.[2] The lines associated with each scatter plot shows the strength of the correlation between instances of that gesture type and modeling performance; the steeper the positive slope, the higher the positive correlation and vice versa. As we can see from the graph, three of the conditions have positive slopes (perceptual feature, movement, and perceptual whole), while two have negative slopes (vague and other). By far the strongest positive correlation[3] is between perceptual feature gesturing and modeling performance ($r = .61$, $p < .025$), while vague gesturing has a weak negative correlation ($r = -.22$,

[2] Data from the three users who dropped out of the study has been omitted from this graph as well as Figure 4.13
[3] All correlation calculations were done using Pearson's Correlation Coeffcient.

$p < .5$). Going back to our earlier table, then, the sharp uptick in vague gestures and mild decline of perceptual features may help to explain why such an increase in gesturing did not result in a similar upswing in modeling performance.

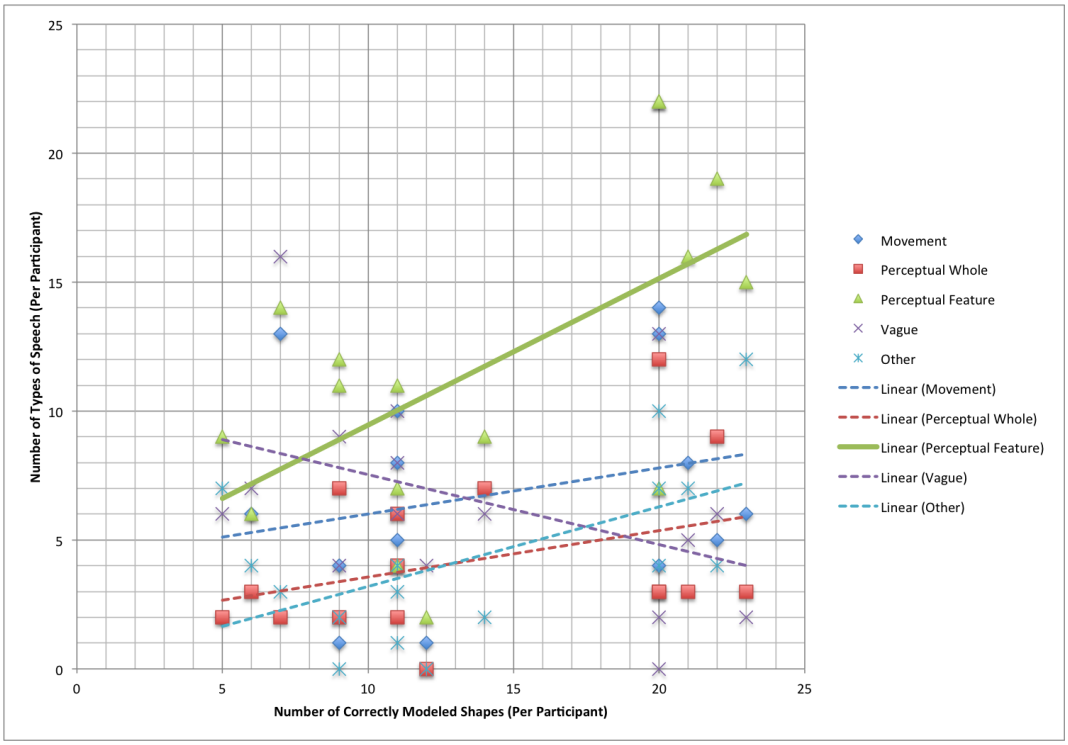

Figure 4.13: A plot of the five types of speech we coded (movement, perceptual whole, perceptual feature, vague, and other) over the number of correctly modeled shapes. The slope of the lines indicate the strength of correlation between each speech type and overall modeling performance.

One might expect that correlation patterns would be similar between gestures and speech of the same type (e.g. instances of movement in gesture would be as correlated to modeling performance as instances of movement in speech), and while we did find some similarities, some surprising differences appeared as well. Speaking about perceptual features was (as with gesturing) the most highly correlated type to modeling success ($r = .58$, $p < .025$), but where gestures marked as "other" had a very weak negative correlation, "other" categories of speech were second most **highly** correlated with modeling aptitude ($r = .56$, $p < .025$) - nearly as much as utterances on perceptual features. Part of this explanation lies in the frequency discrepancy between "other"

gestures, of which there were only seven, and "other" speech utterances, of which there were ten times more (70). The other (pardon the pun) part of the explanation lies in the fact that we have many more words with specific meanings than gestures that are precisely defined, so (for example) explanations referring to looking at the software itself (e.g., "I looked at the screen and it looked like it"), or reasoning about the nature of how the mode works (e.g., "Since it was path I knew it would work"), or internal operations (e.g., "I just look at it and see it"), are harder to perceive in gesture. A possible relation to the potential for specificity in speech lies in the stronger observed negative correlation between modeling ability and speech marked as vague ($r = -.41$, $p < .25$), compared to gestures marked as vague ($r = -.22$, $p < .5$), indicating (perhaps) that a failure to speak specifically (given more abundant options) is more harmful than a similar failure when gesturing.

4.3.3 Observations

A few notes on the above findings are worth making here. Broadly speaking, the study indicated many positive outcomes: overall modeling ability went up while average modeling time went down, the participants improved on every modeling mode in the second session, there was a net positive performance on the second mental transformation task when compared with the first, and participants were generally engaged by the experience, which for most subjects was their first computer-based 3D modeling experience. However, even though no user saw the same device or shape twice, it is as yet unclear how much of the improvement might be contributed to a "practice effect". Due to the "drop-in" nature of the user study environment, the time between each single participants' sessions varied, based on their attendance and availability (i.e., in some cases users had homework or other activities to finish).

We observed some moderate correlations between types of speech and gesture and modeling success, though not necessarily the kinds of correlations we might have expected based on prior related studies. Nor were speech and gesture correlated to modeling acumen in the same ways - some types of gesture were less effective than their corresponding spoken elements, and vice

versa. In some cases, the results were observed were counter-intuitive - such as the anomaly in average modeling times of subjects when using the minimal spanning tree mode, the fact that boys performed worse during the second modeling session while girls performed much better, and that some subjects performed worse on the second mental transformation task, even though they were arguably "primed" by going through the modeling exercises beforehand. Also unexpected is the sharp decline in performance on the PopCAD device in the second session - over 10% - especially after such a high percentage in the first round and given more "experienced" users in the second session. Equally surprising, given a rather unimpressive first round performance, is the sharp increase in modeling success on the SnapCAD in the second round (a jump of 12%), so much so that when coupled with the decline in PopCAD performance, we may wonder on the possible disparity between the groups in "inherent" ability for these kinds of tasks. Another possibility is of course that the order in which subject encounter the devices is more important than we had originally surmised - perhaps the users who started with PopCAD did better on the SnapCAD (and overall) **because** they started with PopCAD. We examine these, as well as the relevance of age and shape complexity on modeling ability, along with a deeper discussion of results across all three studies in the following chapter.

Chapter 5

Discussion

We devote this chapter to a deeper look at some of factors that may (or may not) shed light on a few of the more perplexing and intriguing observations made through the user studies mentioned in the previous chapter, as well as a meta-review of what, if anything, we may conclude based on our reported data and observations. We spend the most attention on our latest study (with the PopCAD and SnapCAD) as it is not only the most recent, but the most significant. That study concerns whether or not our devices can be used effectively for modeling by novice users as well as touching on the relationships between our devices, spatial reasoning, and embodied cognition. We start with the significance of the gesture and speech observations made in the PopCAD and SnapCAD study, discuss the role of age in relation to modeling performance, followed by an analysis of the effects of shape complexity on modeling acuity, a closer look at the error coding we performed, and finally some meta-analysis of the observed data over the three user studies described in the last chapter.

5.1 Gesture and Speech Significance

The work of Ehrlich[41], Levine[91], and Goldin-Meadow especially[60][61], serves as a rough guide to our most recent study design, as they touch on the role of gesture in determining spatial reasoning performance, and later provide strong evidence that gesture is a valuable window into the mind, all of which supports the notions inherent in embodied cognition - that body and mind are far more tightly linked than we have traditionally be led to believe. As we operate under these

assumptions as reasoning to create tangible, physically involved interfaces (as opposed to pure 2D software) it is worth taking a deeper look into how our study results compare and contrast with this earlier work.

Ehrlich and Levine's studies focus on the gestures and speech produced during children's explanations of how they solved a series of mental transformation tasks. The participants were presented with the same sorts of instruments used in our PopCAD and SnapCAD study, although our studies differ significantly in several ways. Of course, Ehrlich and Levine had no devices, and evaluated the speech and gestures produced in explaining the mental transformation task, whereas we examined the strategies expressed when modeling on the PopCAD and SnapCAD. Apart from one practice condition where wooden blocks were used (which in their study had no effect) all of the tasks in [41] were based on 2D paper representations, and the subject had no physical contact with any of the objects they were trying to model. In our study, subjects were handed a 3D-printed (and thus 3D) model of the shape they were attempting to reproduce. Additionally, in Ehrlich and Levine's studies, subjects were instructed to (in their mind) "move the pieces together" or to "observe the movement" of the pieces as manipulated by the experimenter. These factors, as well as differences in age (our subject population was 5-13 years older than those in [91] and [41]) likely contribute to (at least of some of) the differences observed in our study. We spend the next two subsections dissecting the similarities and contrasts in our results compared to the finding reported by Ehrlich, Goldin-Meadow, and Levine.

5.1.1 Contrasts

Given the differences Ehrlich's study and own our own, it is no surprise that our findings should differ. While the gesture and speech analyses occurred while subjects were explaining a modeling strategy, the type of modeling activity they had been asked to perform was substantively dissimilar. As noted above, subjects in our study were handed physical, 3D models of the target shape they were tasked with modeling, and could hold on to that object (and rotate it, look at it from different angles, hold it in front of the device or the computer screen, etc.) during their

modeling process. Afterward, when asked about their strategy, they still had that object, and often gestured to it (or with it) and (of course) talked about it. No such "hands-on" activity was involved in the studies we reference above, nor (as we note later in the chapter) could we find substantive work involving such manipulative activities to examine spatial reasoning ability.

We contend that the "embodied" nature of the tasks in our study help explain some of the differences in gesture and speech patterns and correlations that we observed. In fact, it is likely that given Goldin-Meadow's body of work and studies involving cognition and gesture, she would concur with us. Furthermore, the way in which the examiner in the above studies introduces the tasks to the subjects involves several direct references to movement (e.g. "In your mind, move the pieces together and then move them back apart"). This is significant, as gestures and speech relating to movement was (in their study) both the most frequent type of strategy expressed but, as far as gesture correlations with task performance is concerned, gestures coded as relating to movement was the only type of response they recorded that was exclusively related to answering the test questions correctly. To take an excerpt from [41] (pp. 1265):

> "Gesturing about moving the pieces was correlated with the number of problems answered correctly ($r = .461$, $p < .001$), but it was not correlated with the number of problems answered incorrectly ($r = .202$, ns). Thus, gesturing about moving the pieces together was uniquely related to correct performance, whereas talking about moving the pieces was not."

To summarize our related findings, then: in our study, gestures about movement were the second most observed expression, after those related to perceptual features (113 to 180); speech about movement was also second to perceptual features in frequency (186 to 107), and neither gesture nor speech was significantly tied to performance in our modeling tasks ($r = .29$, $p < .29$ for gesture, $r = .27$, $p < .32$ for speech). Instead, we found the highest correlation (and highest frequency) in speech and gestures relating to perceptual features ($r = .61$, $p < .025$ for gesture, $r = .58$, $p < .025$ for speech). Ehrlich found only a negative correlation between modeling performance and perceptual feature coding, both from speech and from gesture.

We are then left to wonder about the rather drastic differences in our findings. What might

account for both the frequency and correlation differences in movement versus perceptual feature strategies? Although of course we cannot know for certain, we hinted at some of the possibilities above: the "embodied" nature of our tasks, having the subjects hold onto an object representative of the solution they were striving for, the participants being' "primed" for certain kinds of responses in the earlier studies, and the differences in age all may account for some of the differences. The kind of mental processes involved in a mental transformation task are not all that different (necessarily) from those involved in modeling an object with the PopCAD (for example) - a robust mental image of the shape in question is likely a boon in either case. However, a model can be built step-by-step, and the results observed and reflected upon. When picking a correct shape in a mental transformation task, one may mentally operate upon features of the shape in a step-by-step manner, but there is no opportunity to reflect upon various strategies, a holistic decision has to be made. In a step-by-step modeling process, it seems common (from the data and from our own experiences and intuitions) for a modeling "step" to focus on a perceptual feature of the shape being modeled (e.g. the next segment in a path or the top point in a pyramid-shaped hull), and to do so in a very conscious way. Additionally, subjects in our study were allowed to continue holding the model while they gave their strategy, providing a ready "facsimile" on which to project their modeling intentions. These factors may have "paved the way" for a high number of speech and gesture about perceptual features of the models, as the step-wise nature of the task and the physical surroundings lead themselves toward thinking in terms of the characteristics of the shapes. Although we observed a high number of expressions coded as movement, there is nothing inherently "movement-oriented" in 3D modeling (ones body moves in using our devices, of course, but models can be created in other ways, e.g. strictly from text coordinates). In contrast, a mental transformation task is, explicitly asking the user to "move" the object, mentally, into the correct formation. Thus it is unsurprising that the examiners in Ehrlich's study repeatedly used the word "move" and appealed to references about movement (as noted above). It is equally unsurprising then, that by using this sort of language and then looking at "movement" as a gestural and spoken strategy, many instances were found, as the task and the instructions surrounding the task are both "movement oriented"

in a way that the modeling tasks in our study were not.

One of the other major findings in [41] and [91] is that significant performance differences exist between genders on these tasks, and are evident at younger ages than previously thought. Existing research at the time claimed that gendered differences in spatial reasoning developed around puberty, but that several studies had challenged this assumption. In either case, gender differences should have shown up in our study based on the age range of our subjects (11-18). Boys did outperform girls in session one of the modeling task, though it was not by a terribly significant portion (4%), they did model faster than the girls in each round of the modeling exercise (by about 7 minutes total in the first session, five minutes overall in the second session), and they produced more speech instances than the girls did overall (275 to 260), although since there were more boys in the study, this advantage is negligible at best. Interestingly, our findings had girls performing better in many areas; they outperformed boys in the second modeling session by 9%, and across both sessions by almost 3%. Despite a disadvantage in numbers, girls produced more gestures (225 to 188) including those most closely linked to modeling success, perceptual features (96 to 84). Girls also produced more speech elements about perceptual features (97 to 89). The results from our mental transformation task have boys and girls performing about equally, with girls edging out the boys by one tenth of a percent (85.3% to 85.2%, respectively).

Was our sample size too small? Most likely, although it would be interesting to perform a larger study with an n closer to what Ehrlich and Levine had to see if working with our devices does anything to mitigate gender effects. Did we have an exceptionally bright group of girls? Probably, though no independent tests were done for intelligence or other factors that would have indicated an advantage - remember, the girls who enrolled in the study averaged almost a full year younger than the boys (13 years, 7 months for girls and 14 years 6 months for boys), so age and experience advantages are unlikely (none of the girls reported any previous 3D modeling experience). Although the nature of the modeling exercises in our study were more piecemeal, possibly allowing girls more of a chance to reflect and correct their mistakes than in the mental transformation tasks,[1] we saw

[1] There is some evidence, relayed in [41], that girls tend to utilize a step-by-step strategy in mental rotation

no significant difference in the MTT tasks we administered (in fact girls did slightly better).

One possibility is that modeling with the sorts of devices we created are somehow more beneficial to girls than to boys; that the spatial reasoning advantages that boys have are either negated, or that the types of modeling exercises we did significantly altered boys' normal spatial reasoning strategies, which has been known to have a detrimental effect on performance[24][95]. Plenty of other possibilities exist (e.g., the girls simply tried harder) and there is no clear way of determining the source(s) for our results, so we hesitate to make any claims. However, we find it encouraging that girls were able to perform (even out perform) when compared to the boys in our study.

5.1.2 Commonalities

Despite the differences mentioned in the previous section, some of our observations did agree (or at least failed to disagree) with the previous studies. In Ehrlich's study as well as ours, the study population improved overall. In each case, girls improved by a markedly greater percentage, whereas boys improved less so, and in some cases performance actually decreased (in our second session overall and in the post-test for Ehrlich's "imagine movement" condition). Movement and perceptual feature strategies were the most common in both studies, with perceptual whole instances far behind. Generally speaking, gesture expressions deemed most "task-appropriate" (per our discussion in the previous section) served as the highest observed correlation to modeling success; perceptual feature gesturing in our study, movement gesturing in Ehrlich's study. This is, we believe, the main "gist" of both these experiments as far as gesture analysis goes - that gesture of a strategy appropriate to the task at hand is correlated with success on that task, more so than speech alone. This holds with the core of Goldin-Meadow's findings, that gesture is a window into the cognitive process and that by analyzing gesture we can gain insight into the mind of the learner.

problems, whereas boys tend to deal with the whole shape at once.

5.2 Age

One of the more profound and noticeable results from the PopCAD and SnapCAD study was the difference in modeling success between the devices in the first round, and how much that difference was erased on the second round. In the first session, users modeling with the PopCAD correctly modeled 75% of the given shapes, the highest percentage of any device in any round. Conversely, those starting on the SnapCAD modeled only 34% of their shapes properly. Given just this data, we might be tempted to conclude that the PopCAD is a much easier introductory device - or that the SnapCAD is insufferably difficult. However, when we factor in the second round data, in which each subject modeled on the device they did not use the first time around, a different picture emerges: PopCAD modelers in the second round modeled 65% of the shapes correctly while SnapCAD modelers achieved a 56% success rate. If we track each group (let us call the first round PopCAD modelers group A, and the first round SnapCAD modelers group B), we would be sorely tempted to declare that the groups themselves are unevenly talented: Group A scored 75% on PopCAD and 56% on SnapCAD, while group B scored 65% on PopCAD and 34% on SnapCAD.

Since we did not perform an intelligence test or any sort of generalizable aptitude test, we are left to guess using other means. Given the massive development (both cognitively and physically) that occurs between the age extremes in our subject population (11 to 18), it would be tempting (and even logical) to assume that the older subjects would perform much better on the modeling tasks than their younger counterparts. As it turns out, the average age of group A was higher than that of group B - but only by three months (group A average age was 14, group B was 13.75). We found a very modest correlation ($r = .39, p < .15$) between age and the number of correctly modeled shapes, suggesting that while not to be overlooked, it may play less of a role then we would have suspected. It is also possible that the statistics are slightly misleading here - the subject population was weighted toward the younger end of the spectrum: the average age was 13.8, while median age was 13.5, and the mode was 12 years old. Meaning the few older participants would have had to perform impossibly brilliantly (i.e., higher than the highest possible

score) for a strong age to performance correlation to show up. In keeping with these findings, we also found no real correlation between age and overall performance on the mental transformation tasks ($r = .23, p < .45$). This data of course does not discount that age plays a factor, nor that group A may have been more talented than group B in the PopCAD/SnapCAD; simply that within rough parameters, age matters, just not as much as one might think. Take for example our oldest participant, an 18 year-old boy. He correctly performed 11 of the 24 modeling tasks, while the four 12 year-old participants scored 14, 11, 12, and 11. Our youngest participant, and 11 year old, reproduced seven shapes correctly, while a 13 year old did five correctly, and a 14 year old got six right.

5.3 Shape Complexity

In order to attempt to judge each shape's complexity, we sought out a previously-defined set of criteria by which to judge "complexity". As it turns out, there is a long and thorough discussion of complexity in relation to **two-dimensional** shapes, starting seemingly with Fred Attneave and Malcolm Arnoult[19][18] in the mid 1950's, who define methods of generating random two-dimensional shapes and examine their physical characteristics in relation to their judged complexity. As it turns out (in [18] as well as others' follow-up work) the "Number of Turns" in the shape was responsible for significant amount (nearly 80% in Attneave's study) of the preceived complexity of a shape. "Number of Turns" is defined as "the number of maxima (regardless of sign) in one cycle of the function relating curvature to distance along the contour. This function is a series of spikes for any angular shape, and a step-function for any curved shape..." (see p. 226 of the aforementioned article). Symmetry, angular variability, and squared perimeter over area also had some effect.

However, as it seems unclear to us how one might adapt a "Number of Turns" rating to a true **three** dimensional model. Many studies claim to have studied complexity in relation to 3D mental transformation tasks, (starting with Shepard and Metzler[131]), but they (as well as the many other studies we found[101][132][140] used perspective line drawings, **not** actual physical models.

This had an advantage for the types of mental rotation tasks they were performing (recognition of matching pairs), but seemed insufficient for the tasks in our study.

This led us to develop (as best we way) a rubric to determine the complexity of the shapes we presented in the study, as a way of teasing out any correlation between complexity and performance. In lieu of attempting an exact number of turns estimate, we included three criteria: (a) the minimum number of lights necessary to guarantee the correct shape,[2] (b) the number of faces (for convex hull models only), the number of line segments (for path models only), or the number of distinct branches (for tree models only), and (c) a symmetry score based on number of lines of symmetry, from 3 (indicating asymmetry) to 0 (indicating three or more lines of symmetry). The scaling for symmetry comes from the belief that indicators (a) and (b) above are more closely aligned with Attneave's "number of turns" metric (being highly correlated to perceived difficulty), while symmetry was much less correlated to complexity (although symmetry did still play a part), so we made the scale as low as possible so that it would weigh less on the overall complexity score of a model. So, for example, a regular octahedron would have six points, eight faces, and a zero symmetry score for an overall difficulty score of 14. The complexity score of each shape is shown in 5.1 next to the number of times it was modeled correctly. The shapes in each session were of course different, but are labeled the same in this table, indicating the order in which they were presented.

Table 5.1: Complexity of Models and Modeling Performance (CH = Convex Hull, P = Path, T = Minimal Spanning Tree)

	CH1	CH2	CH3	CH4	P1	P2	P3	P4	T1	T2	T3	T4
Session 1												
Complexity Score	14	19	19	19	7	18	20	24	9	13	17	17
Performance of 19	8	13	8	11	17	14	8	9	12	8	8	11
Session 2												
Complexity Score	12	20	15	13	14	14	18	17	21	17	16	25
Performance of 16	7	9	11	11	11	13	8	12	7	11	7	9

[2] In minimal spanning tree models where a placement of lights results in several possible correct formations, only one of which is the desired shape, we add points necessary to "force" the correct representation.

One might expect to see a strong negative correlation between a given model's complexity score and the number of subjects who were able to model it correctly, however the observed correlation was only moderate: $r = -0.41, p < .05$ over both sessions, indicating that while shape complexity (at least as we have calculated it) is significantly correlated, it plays only a moderate role in determining modeling performance in our study.

5.4 Freehand Modeling

At the end of both sessions, the subjects were given the opportunity to model a shape of their own design, using any of the modes presented during the modeling exercises. Each participant modeled after the first round, and then were given the opportunity to create a different shape after the second round that they wanted printed out instead (most subjects stuck with their original model). The prints from the 16 participants who finished the study are shown in Figure 5.1.

Figure 5.1: A collection of the child-designed objects from the PopCAD/SnapCAD study.

Objects were created using all three modes, though only one participant chose the convex hull mode for their object; nine subjects used the path mode, while six used the minimal spanning tree mode. It should be noted that almost every participant explored all three modes on their own

before settling on one they liked the best. Choices were sometimes based on strategy (e.g. only one mode was capable one making the shape they envisioned) while many users simply explored different modes and patterns until something struck their fancy. As evident in the picture, some users went with letters (usually the initial of their first name), others attempted to create a symbol they knew (e.g. one participant attempted the "Tri-Force" symbol from the Zelda video game franchise), and others (as hinted at in Figure 5.1) simply turned points on and off until they achieved an aesthetically pleasing object.

Of the 24 user-created models (19 from the first session, 5 more from the second session) we received an even number generated from each device (12 apiece). We were curious to see if, on the SnapCAD models, users took advantage of the greater expressive power offers by the larger input space (a 7^3 grid compared to a 3^3 grid). Of the 12 SnapCAD models, 9 of them would have been impossible to model using the PopCAD (without substantial use of the editing mode, at least).[3] Of the five users who chose to model a new shape after the second round, four of them had used PopCAD in the first round and SnapCAD in the second round. Three of these four users modeled shapes they would not have been able to using PopCAD. However, based on the difficulty rubric laid out in the previous section, the average complexity of shapes modeled on the PopCAD was actually higher than that of SnapCAD (22.83 to 18.50). Interestingly though, the shapes with the three highest scores (all from PopCAD) were from users who chose to model different shapes after the second round in order to use the SnapCAD - but to create a "simpler" shape (i.e., a shape with a lower complexity score). Granted, there are some mitigating factors at work here - on the PopCAD interface, it is fairly straightforward to turn on all 27 points - it is a simple touch of the finger, the lights are already placed on the towers. On SnapCAD, more effort is required to take a tower, place it into a socket, take an LED board, and then snap it onto a location on the tower. In fact, several of the high scores we just referred to were generated by users simply turning on all the lights with path or tree mode active. If we compare the set of PopCAD models without

[3] Two notes here: (1) We counted the shape as impossible if any vertices would have to change planes to create the shape; (2) Any shape modeled on PopCAD can, of necessity, be recreated on SnapCAD.

those models dropped in favor of SnapCAD models after the second session, the shape complexity average drops to 16.75 - a few points less than the SnapCAD average.

Interestingly, most of the "intentional" models - those models created from a firm mental model or notion of what the final shape should be - a preferred strategy was to use the path mode and a singular vertical plane (e.g. the first row of three towers on the PopCAD) to treat the device essentially as a 2-dimensional drawing tool. We can see (in the figure above) shapes like the star, or the letter "s" - while they print in 3D of course, the modeling necessary to create these shapes happens in 2D. Also of note is that the users overwhelmingly chose a vertical (as opposed to horizontal) plane in which to work. When we imagine ourselves drawing or writing, it is almost along a flat horizontal surface (except perhaps when writing on a whiteboard or painting on an easel), so why the preference for verticality? While we cannot know for certain, it is true that some amount of verticality is implied in the device - the towers themselves rise in vertical columns above the "floor" of the device. Additionally, the average time writing manually as opposed to typing on a computer has significantly decreased in recent years, so perhaps the vertical screen of a computer somehow relates. In any event, using the device as more of a 2D drawing instrument is a somewhat unexpected, but nonetheless welcome observation.

The freehand modeling session (or sessions) were quite clearly the most enjoyable for the users themselves. None of the participants refused to do the freehand modeling session, or quit in the middle of it. In fact, many subjects went over the allotted 10 minute modeling window exploring, testing ideas, rearranging point configurations, and generally being absorbed by the experience, which we found encouraging (and of course we allowed subjects to play as long as we could). This suggests some viability for a device like this in a classroom (especially one with a desktop 3D printer), where students could simply play with the interface, observe the interactions between 2D and 3D representations in a fluid manner, and print their own creations with the click of a button.

5.5 Error Analysis

For each modeling task, one (and only one) of seven error codes was recorded, based on the outcome of the task. A more complete detail of the error codes can be found in table 4.1; this section focuses instead on what significance (if any) these error codes have on our observations[4] . To briefly recount the codes and their associations, then: C = correct, EP = error in proportion (general shape is correct, but model is too tall, too wide, etc.), E1 = error in recognition (subject had the correct shape but did not recognize it), E2 = error in belief (thought the shape was correct when it was not), E3 = error in implementation (knew shape was incorrect, but knew why), E4 = error in strategy (subject knew shape was incorrect, but could not explain why), I = incomplete (includes giving up, asking to move on, running out of time).

Table 5.2: Error Code Breakdown. C = Correct, EP = Error in Proportion, E1 = Error in Recognition, E2 = Error in Belief, E3 = Error in Implementation, E4 = Error in Strategy, I = Incomplete.

	Total	*Session* 1	*Session* 2	*PopCAD*	*SnapCAD*	*Girls*	*Boys*
C	243	127	116	152	91	100	143
EP	44	19	25	16	28	20	24
*E*1	1	1	0	0	1	1	0
*E*2	50	28	22	20	30	13	37
*E*3	2	2	0	0	2	0	2
*E*4	17	9	8	7	10	6	11
I	63	42	21	21	42	28	35

As we can see from Table 5.2, several types of errors barely occurred (errors in recognition and errors in implementation), while others were more common (proportional errors, belief errors, and incomplete tasks). As a designer, it is comforting that errors in which the user had the correct answer but was unable to recognize it and errors in which the subject knew the correct strategy to model the shape but could not implement it (E1 and E3, respectively) were minimal, as these errors seem to point more towards a failure of the interface (the software representation

[4] Again, this data is from the PopCAD/SnapCAD study only.

being unclear, or the modeling mechanisms being hard to use) as opposed to genuine difficulty in modeling the shape. Interestingly, although not significant statistically because of their sparsity, E3 codes actually had a mild positive correlation to modeling success ($r = .31$, ns), possibly indicating that correct expression of strategy in cases of error are positive pointers towards modeling success in other cases.

Incomplete codes tell us little about the beliefs or modeling strategy of the user beyond an inability (or unwillingness) to model the shape in the given time. Unsurprisingly, "I" codes present a very high negative correlation with modeling success, as no other strategy code could be applied ($r = -.825$, $p < .001$). As we might have guessed, a bad strategy is better than none at all: code E4, where users knew their model was incorrect, yet expressed a strategy (albeit one that would not have yielded the correct solution) was still negatively correlated with overall modeling success, but less so than "I" coded results ($r = -.610$, $p < .013$). E4 codes also carried a weaker negative correlation than E2 codes, where the user mistakenly believed they had modeled the shape properly (unlike in E4 codes, where the user was aware the shape was wrong). E2 codes were the second most negatively correlated error to modeling success ($r = -.764$, $p < .001$).

While developing the coding system described above, it seemed important to separate instances where the modeler had modeled the shape properly **except** for an error in proportionality, instead of simply lumping them into the E2 code. This kind of error was fairly common, occurring 44 times in our study, and seemed to represent its own unique category, although we were unable to find related literature to support this. However, of the categories with more than a few instances, errors in proportion were the least negatively correlated to success on the modeling tasks ($r = -.235$, $p < .390$), somewhat justifying our belief that errors in proportion only were of a different breed of mistake. This likely stems from the fact that unless a user asked directly if proportion in the models mattered, they were not told that it did. This means that several users who repeatedly made EP errors may have been able to fix their models had they known that proportionality was a factor. Occasionally, during the explanation of their modeling strategy, users who had an EP error would realise or express that they could have modeled the shape more accurately (and

sometimes even fix it on the spot), in which cases modeling times and error codes were adjusted accordingly. Although we cannot present direct evidence why errors in proportion are less harmful than the other sorts of errors we recorded, it does seem somehow intuitive to us that this should be so; a triangular prism that is wider than the model presented is still a triangular prism - it is not a cube, or tetrahedron - there is not an error in "kind" - merely one of scale. A mismatch in proportion only seems to imply a greater degree of understanding and modeling ability than simply misrepresenting the intended shape completely, and the data we have collected seem to bear this out. Although none of these findings are particularly surprising on their own, it is worth noting that the kinds of errors modelers make are very often indicative of their overall performance.

5.6 Cross-Study Comparisons

The three studies mentioned in the last chapter are quite different in most respects. The first two UCube studies have much more in common with each other (obviously) than with the PopCAD/SnapCAD study, yet it is worth looking at the results from all three to investigate what, if any, larger patterns emerge.

Table 5.3: Cross Study Comparisons.

	Subjects	*Ages*	*Modeling Modes*	*# Models*	*Correct*	%
UCube Pilot	14 (6 groups)	12-14	Convex Hull	5	24/30	80%
$UCube\ Follow-Up$	10 (indiv.)	11-13	Convex Hull	5	41/50	82%
PopCAD/SnapCAD	20 (indiv.)	11-18	C.Hull, Path, Tree	24	243/420	57.9%

When we compare raw modeling performance across studies, we see the first study resulted in 80% (24 of 30) correct models, the second UCube study resulted in 82% (41 of 50), while the third study resulted in only 243/420, or about 58%. The last study is of course the outlier, but the above table includes models from the other modes (Path and Tree), that the other two studies did not examine. If we compare only across convex hull modeling tasks, the PopCAD/SnapCAD study yields eight models across both modes, with 78/140 convex hull tasks modeled correctly, or 56%.

While much lower than the earlier studies, this number still ignores the differences between devices. Convex hull models on the PopCAD were correct 30/40 times in the first round and 17/32 times in the second round, for a total of 47/72 for a little over 62%. SnapCAD produced 10/36 correct models in the first session and 21/32 in the second round, or 31/68 or abut 46%. Interestingly, neither of these numbers is particularly close to the convex hull success we observed in the earlier UCube studies.

What might explain this discrepancy? Are the PopCAD and SnapCAD devices really that much harder to use, or could there be another explanation? One possibility worth looking at is the shape complexity metric we developed in the previous section, as we noticed a moderate negative correlation between shape complexity and modeling score, suggesting that if we the models were much easier in the easier studies, some of the difference in score might be attributed to that relationship.

As a brief reminder, then: the complexity score for a convex hull is the sum of the number of points and faces plus a symmetry score (three points for asymmetry, two points for one-axis symmetry, one point for two-axis symmetry, and no points for more than two-axis symmetry). To report the complexity scores (breakdown of points, faces, and symmetry score is given for the two studies not previously disclosed):

$UCubePilot$: 2 (2+0+0), 2 (2+0+0), 14 (8+6+0), 12 (6+5+1), 11 (4+4+3)
41 / 5 = 8.2 complexity average

$UCubeFollow{-}Up$: 14 (8+6+0), 8 (4+4+0), 14 (6+8+0), 18 (9+9+0), 18 (9+6+3)
72 / 5 = 14.4 complexity average

$Pop/Snap$: 14, 19, 19, 19, 12, 20, 15, 13
131 / 8 = 16.375 complexity average

While the PopCAD/SnapCAD study did in fact have the greatest average complexity score, it beat out the highest performing study (the UCube follow-up) by less than two points. Given the 20% plus drop a two-point difference does not seem to be able to explain it all, especially given that the highest performing study did not have the lowest complexity score (the first pilot

did). However, one mitigating factor may be that four of the shapes in the PopCAD/SnapCAD study were harder than the hardest shapes encountered in the UCube follow-up study. It could be that performance is relatively linear up until a certain complexity point, after which it drops dramatically. We also used more "standard" polyhedrons in the UCube follow up, many of which have a "deceptive" complexity score; a cube, for example, may be the easily recognizable and most easily modeled shape (it was in the UCube follow-up study), but it has a complexity score of 14, more than the "right-angle" off centered pyramid we used in the PopCAD/SnapCAD study. Moreover, we did not use a cube in the PopCAD/SnapCAD study, while it was used in both of the UCube studies. Another possibility is that, given the smaller sample size and fewer models, we simply did not take a large enough sample in the first two studies. The pilot had six groups over five shapes (30 tasks), the follow-up UCube study had five tasks with ten individuals (50), while the PopCAD/SnapCAD study had four tasks over 19 individuals in the first session and four tasks over 16 individuals in the second round for a total of 140 tasks - almost three times the size of the UCube follow-up. It is possible that if we had performed a larger number of tasks in the earlier studies that the performance numbers would start to move closer to what we observed in the PopCAD/SnapCAD study.

Finally, one last factor to take into account here are the subject demographics. Only two participants in the PopCAD/SnapCAD study had indicated previous experience with 3D modeling in any capacity, and the study site was a drop-in program serving primarily disadvantaged youth in a predominantly low socioeconomic neighborhood (indeed, one of the neighborhood schools was scheduled to close permanently while we conducted our study). In contrast, the two earlier studies with the UCube were performed at a fairly affluent, predominantly Caucasian middle school, with students from a multimedia class, most of whom had been exposed to 3D modeling software (like Google SketchUp[135]) as part of their classroom multimedia curriculum. Additionally, the UCube follow-up study was skewed in gender more so than the other studies (eight boys to two girls) and since boys tended to do better on modeling tasks, especially upon their first interactions - the UCube studies only had one session - this gender balance may have played a role in the modeling

performance we observed. Although these factors are merely speculative, the observed performance (in the 80% range for the middle school subjects and less than 60% for our drop-in program), is likely not all due to innate modeling ability, differences in shape complexity, or the use of the UCube device specifically.

5.7 A Note On Other Uses

Thus far we have focused on our devices as a means of engaging novices in design for 3D printing. However, that is not the only (or potentially even the best) use case for these instruments. From a pedagogical perspective, it is easy to think of several areas to which devices like ours may be well-suited. In mathematics instruction, the grid-like properties of the interfaces seem to be a very "natural" way to introduce (for example) 2D and 3D coordinate systems, simple linear graphs, the notions of slope, axes, and origin, geometric shapes (like a cube or a trefoil knot) and relations (like perpendicularity or symmetry), and many more. In chemistry, molecules could be visualized using the minimal spanning tree mode; in astronomy, constellations could be modeled. More literally, in art, base components could be made for sculpture and scale models of bigger pieces; architecture students could print out basic shapes for their building structures and scenes. The diversity of use cases underscores how powerful these sorts of devices (even the simple ones) can be. In the following chapter we discuss in more detail a few more ideas about what the future of embodied fabrication devices might look like.

Chapter 6

Vision and Future Work

In this chapter we discuss a broader vision of embodied fabrication, expand on the ideas presented so far, and present several possibilities for future developments in our own work and for embodied fabrication more generally. Crucially, the work presented in the preceding chapters need not be taken as representative of embodied fabrication devices in terms of design, functionality, or purpose. The devices we created, while giving birth to this notion of embodied fabrication devices only cover a small swatch of the potential landscape. To elucidate: we focused on novice designers (we could have focused on experts or somewhere in between), we aimed our designs at middle-school aged children (we could have aimed younger or older), we could have focused more on inclusive design for those with physical and cognitive disabilities, we focused on 3-dimensional design with 3D printing as the fabrication output - one could have worked on ways to turn 2D designs into 3D-printable objects, or on flattening 3D files into slice forms suitable for a laser cutter, or on embodied output for CNC machines, sewing machines and e-textiles, or even standard shop tools for wood and metal. Some of these ideas are already close to reality, as mentioned in the chapter on related work, and if current trends in desktop fabrication continue, we will no doubt see other possibilities arise.

Even in terms of constructing tangible interfaces for novice 3D design, we have only scratched the surface. Indeed, we rejected many other possible designs in choosing the physical format for our devices; the UCube, SnapCAD, and PopCAD, while they may appear quite different (and are in many ways) they all operate off of the same general paradigm: a set of vertical towers

with actuators that communicate integer coordinates via LEDs that connect to a piece of software which takes care of most of the visualization and modeling algorithms. Although we had some success with this formula, it is far from the only one we considered (and of course there are many potential designs we failed to think of). While working within the integer lattice on step-by-step, very intentional interfaces provided some worthy advantages and a remarkable range of output considering the restraints, one could have gone many other directions.

To provide a truncated list of the many ideas we had and suggestions we received: various means by which to perturb the physical points off the integer lattice, through sliders, potentiometers, force sensors, resistor networks, etc.; using some sort of lateral connection or visualization to make horizontal connections more apparent, by electroluminescent wire, e-textile strips, or reflected light; to forgo the hardware and use a 3D camera, 3D scanner, or mobile phone combined with computer vision techniques to read in real-world objects, clay, or some other modeling material instead of switch states from a device. We had our reasons for not implementing some of these (to avoid blocking movement through the modeling space, the desire to maintain a tangible interface) but that certainly does not mean that these ideas could be implemented very effectively in other embodied fabrication devices. Indeed, several of the limitations of our devices, noted earlier, could be resolved with some of these different approaches - modeling curves, complex shapes with many input points, geometric shapes off the integer lattice - and undoubtedly others could think of even more innovative interfaces in this area.

6.1 Short Term Improvements

From these myriad ideas, we move on to discuss some of the more direct future work that could be done with our devices. Starting with SnapCAD, then: given the ability to relate different colors, and thus represent multiple shapes or players, we have yet to really explore this area. We envision not just a modeling apparatus, but a platform for 3D spatial interaction that goes well beyond the “tic-tac-toe” and sample modeling game we discussed in chapter 2. Additions could extend the number of players and colors to three, four, or five, we can implement new modeling

modes or functions that take advantage of multiple shapes, such as taking the union, intersection, or difference of two or more convex hulls. Additionally, the towers we designed originally do not need to be the only "input objects" - one could imagine a number of different objects also being able to slot in to the same interface, and depending on which object the software was expecting, the software could change its behavior accordingly. One might imagine towers that provided sonic feedback, and could take in and replay audio samples, creating a sort of 3D spatial sequencer. One could outfit towers with different sensors such as reed switches (which detect magnetism) - thus giving the SnapCAD the ability to graph a point cloud representing the strength of a particular magnet placed in the middle (or anywhere near) the device.

As for PopCAD, 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. To start with the obvious, our device could be expanded to include a larger array of input points (5x5x5, say), we could potentially find a way using tiny magnets or magnetic paint to achieve a similar "snap" effect as in SnapCAD, which would allow for the same kinds of multiple color/player interactions discusses above. 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). A deeper look into paper engineering and origami may yield some surprisingly dynamic structures. These structures might be amenable to additional sensors or hardware that could be embedded into the paper or the book to provide new functionality (rotation, proximity, pressure). Additionally, due to the inexpensive and portable nature of the PopCAD design, 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 by "snapping" several PopCADs together, 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. It is also worth looking at redefining or expanding what "paper" means as a material and what kinds of things can work with it. Although

not yet available, there are "circuit stickers" made from a very thin and flexible substrate and designed specifically to be used with paper, copper tape, and the like. While various types of "conductive paper" are available, they are mostly designed for custom scientific applications, and lack the sort of "hackable" potential that a conductive paper for electronic paper-crafts would ideally have. Given that paper can be made at home (or in a school lab or even classroom), it seems likely that an electronics friendly recipe from the maker community before too long. If a stencil-like method became available for finely separating conductive and non-conductive elements while making a single sheet of paper, then we have truly arrived at paper-based circuit boards. One can imagine a desktop 3D printer being able to lay down thin layers of pulp in conductive and insulating varieties to build, in-situ, a 3D paper circuit.

Due to its inexpensive nature, the PopCAD makes a good candidate for a DIY kit, whereby the design files for the paper elements, the schematics for the circuitry, and the harder-to-find components (like the fabric tape, LEDs, and microcontroller) could all be packaged together and sold under an open source license. As the democratization of technology is one of the goals of this work, it seems fitting that an inexpensive, open-source kit be one of the results of our research. Without including the paper, scissors, or soldering equipment, we estimate that the components for a PopCAD kit would be roughly $6US for the LEDs, $20 for the conductive tape, and $30 for a microcontroller, for a total of roughly $60US with tac and shipping. $60 may still prevent some educators from purchasing a device, but certainly not as many as a $500 device would. With that in mind, we plan to redesign the PopCAD with a kit in mind - making the circuit more straightforward and the construction more robust, while developing solid documentation and instructions for distribution with the kit.

For the software, several less-fanciful or inspiring opportunities arise that would nonetheless make significant improvements to the existing state of affairs. The current software is written in Java, and as an application would have to manually installed on any computer that wished to make use of it. Porting the software to JavaScript and making use of new developments in HTML5 that greatly enhance a modern web browser's ability to display complex, interactive 3D graphics

would allow the application to be accessed from anywhere. It has also become easier to connect peripherals attached to a home computer to an application running in a web browser. There are many different Ethernet shields available for Arduino, as well as the Arduino Yun, a single board the combines an Arduino with a Linux-based operating system with WiFi and Ethernet support. There is even a web-based integrated development environment (IDE) for writing and uploading code onto an Arduino straight from a browser[8]. Combined, these methods would allow users all over the world to run a local copy of the software, configure it for their own uses, and receive and install the latest firmware versions of the Arduino code. There is one advantage of the software currently being in Java, however - the Android mobile operating system uses Java, so a mobile phone and tablet-based version of the software could be made available with a little work, allowing those without a desktop or laptop computer (or those who wanted to take a PopCAD camping with them) to still make use of our contributions.

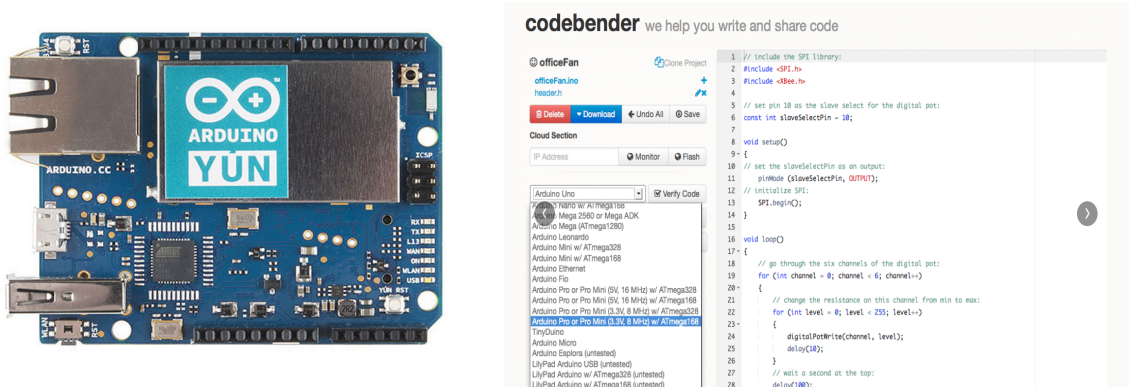

Figure 6.1: Left: The Arduino Yun, an Arduino board with a Linux-based OS. Right: codebender.cc, an open-source, web-based platform for writing and uploading code directly to an Arduino.

Additionally, we feel there is a fair amount still to explore in the video footage we captured from the SnapCAD / PopCAD study. We recorded over 400 video clips of participant modeling and 40 hours worth of screen capture from the software during that time. We looked at modeling results and the gesture and speech expressions made when answering a certain question about modeling, yet there are many more things we could analyze given the time. For instance, recording and coding

the gestures made during the modeling process; does gesturing while modeling correlate to modeling success, or to gesturing while explaining modeling strategy? We could have done analysis on the screen capture to see if subjects who interacted with the software more often were more likely to be good modelers. We could look at the types of orientations the users put the software in and detect any correlation between the amount of time spent in certain orientations versus modeling success. These are questions we believe are worth exploring, however the time and resources available to us have not allowed such a thorough analysis to be completed.

6.2 Extending Embodied Fabrication

As we alluded to at the beginning of the chapter, the work we have presented is but a minnow among whales compared to the potential work on embodied fabrication research. We have given some concrete instances of improvements or changes that could be made to our existing devices and software, without indicating (however imperfectly) what might lay ahead for those interested in embodied fabrication more generally.

The core ideas in our work deal with creating means of increasing accessibility to and understanding with emerging fabrication technology while maintaining a sense of authorship and empowerment in the user, by leveraging the deep connections between body and mind. These strands might be woven together in any number of different ways and with greater emphasis on some aspects than others. By breaking down these elements we might think intelligently about how focusing on one of these might play out in relation to the rest.

In focusing on accessibility, we might envision devices created to give a greater sense of 3D modeling to those with severe vision impairments, perhaps with a combination of familiar materials such as clay or play-doh and wearable haptic devices. We might think of ways to take input from those with limited motor skills and transform it into potential output for 3D printers and laser cutters - see for example the EyeWriter project[9] in which a group of technologists developed a set of glasses for a former graffiti artist who had been diagnosed with ALS (Lou Gehrig's disease) and only had free movement with his eyes. The glasses would track eye movement and allow eye

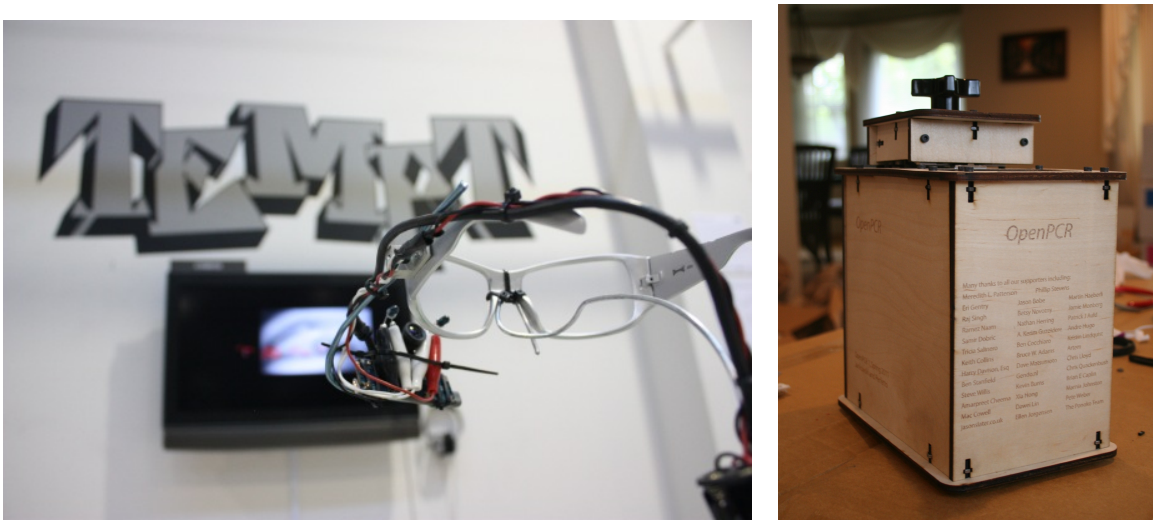

Figure 6.2: Left: The EyeWriter, a wearable eye-tracking system connected to a paint program that allows users with ALS (or other forms of paralysis) to paint. Right: The OpenPCR, an affordable, open-source polymerase chain reaction (PCR) machine that can be used at-home for DNA replication, gene sequencing, and more.

movements to control a drawing program, allowing him to create artwork again. We can imagine a similar set of devices for the creation of artifacts for 3D printing, laser cutting, sewing, or even circuit design.

Another interesting thought comes from the DIY-biology movement, which has released (and continues to work on) ways of creating affordable polymerase chain reaction (PCR) machines, used for DNA replication, sequencing, and analysis. The OpenPCR[10] is a completely open-source PCR machine currently available for $600 (a fraction of traditional lab versions, much like industrial 3D printers). Imagine creating an embodied interface that teaches children how DNA replication and gene sequencing works!

To summarize, while there are some concrete steps to take in our own work, the vision for embodied fabrication devices, while incredibly exciting to think about, is far too open at this stage to offer more than mere speculation. We can only hope that other engineers, designers, artists, and scientists continue to work on objects and technologies that spur others to create ways of connecting their inventions to people in ways that inspire, empower, and enlighten.

6.3 Closing Remarks

During the four years since beginning work on the first UCube prototype, our thoughts and beliefs about the nature of our work evolved, became steadily more focused and resulted in the work we present here on devices for embodied fabrication. Over the course of designing three devices and three user studies, we gained valuable insight into how young people think about 3D modeling, how they interact with never-before-seen tangible devices, the kinds of models they create, and the strategies they use (both verbal and gestural) to explain their modeling decisions. This chapter is devoted to "taking a look back" at the body of work that comprises this thesis and attempting to distill the most relevant and unique findings into their most basic parts.

We have created three separate, fully-functional prototype devices, the UCube, SnapCAD, and PopCAD, each of which interfaces with a piece of software (again, that we created) that allows one to specify points in 3-space in various ways to create 3-dimensional solids that can be easily exported into a 3D printable format. We are aware of no other systems that combine the physical, embodied nature of our designs with the express purpose of making design for 3D printing accessible to novice designers as young as 11 years old.

We performed three separate user studies with over 50 hours of subject interaction with our devices and over 40 different subjects, aged between 11-18 years old. Our first two studies showed that the UCube can be used to reproduce convex hull models both from on-screen representations and from 3D printed physical models. We also ran a matching task that strongly indicated that children have the ability to mentally reconstruct and accurate convex hull from a set of lighted points in 3-space. Our last study, a two-stage evaluation of the PopCAD and SnapCAD, looked not only at convex hull performance, but at path and minimal spanning tree modeling as well. Additionally, we had subjects do a mental transformation exercise before and after the study to assess spatial reasoning skills. We analyzed video recordings and coded the speech and gesture expressions produced when participants were asked about their modeling strategy. We observed improvements in each of the three modeling modes, improvements in the mental transformation

task scores, and an increase in speech and gesture expressions from the first to second sessions. Most encouraging was the dramatic improvement we observed from girls over the course of the study. We found correlations between the types of gesture and speech produced and overall modeling ability, and based on prior research, we concluded that subjects who exhibit a high number of gestures that are classified as most relevant to the task at hand are in fact the most likely to perform well on that given task. Interestingly, we found only a modest correlation between age and performance, while an analysis of performance against shape complexity found a more significant correlation.

Perhaps most importantly, children were deeply engaged by the devices. They took advantage of an open modeling session to create a wildly diverse set of objects, many taking longer than the allotted time just to explore the possibilities of the interface. This is crucial given the fact that the subjects in all three studies were given very minimal instruction on how to use the device, and no instruction on how to **think** about the relationships between the physical device and the software. The ability of the devices to engage youngsters in exploratory play will allow them to come to their own conclusions about how to operate the interfaces most effectively, and will no doubt lead to unforeseen adaptations and use-cases. The engagement we witnessed indicates to us that an interface such as the ones we have devised would likely be a welcome addition to many educational spaces, and even some homes (many kids we worked with said they "wanted one"). Is it our hope that this work will continue on in such a way as to fulfill these children's wishes, with the creation of ever-more engaging, expressive, and diverse tools that combine thinking with the mind and acting with the body to bring a deeper level of understanding and learning to the full breadth of human experience.

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Appendix A

Conference Posters and Visualizations

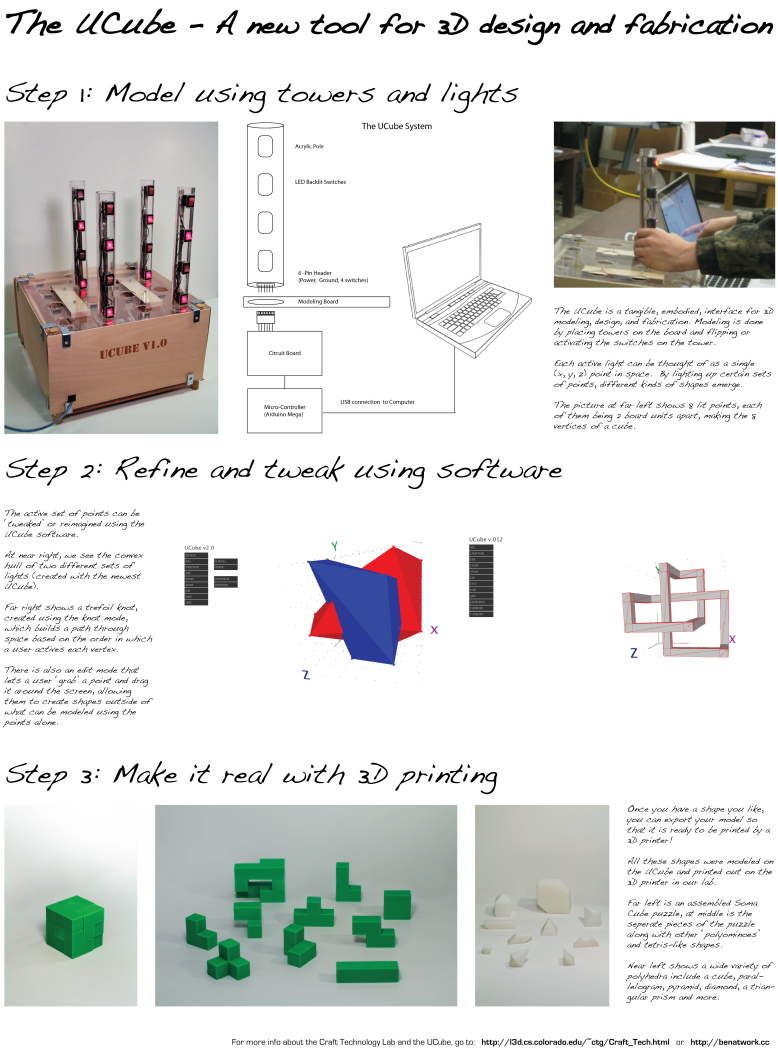

Figure A.1: The poster used at the presentation of the UCube at the Denver Art Museum.

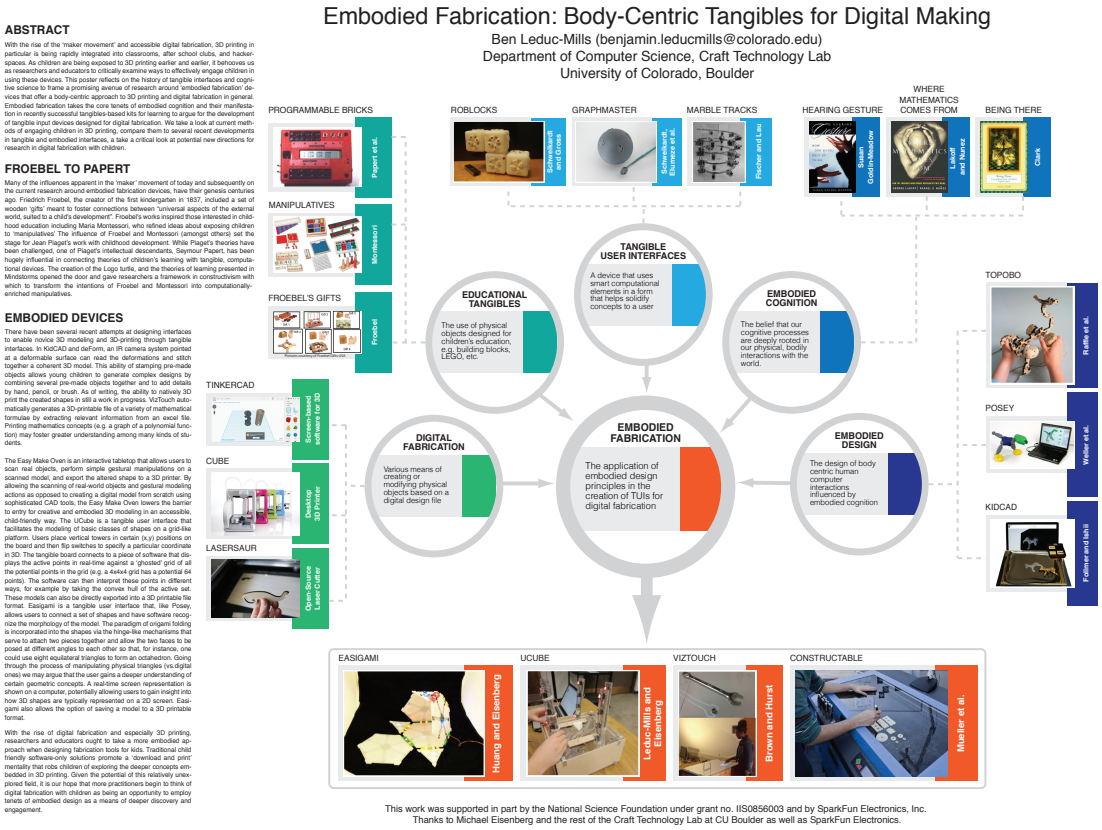

Figure A.2: The poster presented at the 2013 FabLearn conference at Stanford University, in support of a short paper by the same name[88].

Appendix B

Selected Transcriptions

This appendix contains several illustrative transcriptions from the third user study with the PopCAD and SnapCAD, where we recorded the speech and gesture expressions of users explaining their modeling strategy. These excerpts contain quotes from users generated while explaining their modeling strategy for a given shape, the observed gestures that occurred during the spoken explanation, and the speech and gesture codes generated from those expressions. A reminder of the codes and examples used are provided in Table B.1.

Excerpt 1

> "It goes upward, downward, over, up,across, over downward, over, and doesn't go up again."

Gesture: (Pointing along sides of the shape)

Codes: S.M, G.PF

- User3, Shape P2, Session 1

Excerpt 2

> "I saw that is was a series of L shapes. . . I just thought that if I could make a series of L, I could soon make it."

Gesture: (rotating model in hand repeatedly)

Codes: S.PW, S.PF, G.V

Table B.1: The various coding strategies used in the video analysis of subjects' modeling strategy explanations. Borrowed and adapted from [41].

Category	*Definition*	*Speech Examples*	*Gesture Examples*
Movement	Any indication of movement	"Just slide them together and then it looks like that" (S.M)	Miming movement with the hands (G.M)
Perceptual Features	Focus on a particular feature of the model	"Because there is a little bend in here and a point thing here" (S.PF)	Pointing to a specific feature on the model (G.PF)
Perceptual Whole	Any indication of seeing the model as a whole	"It looks like an arrow!" (S.PW)	Gesture indicating inclusion of the whole shape (G.PW)
Vague	An expression of strategy that the coder cannot decipher	"Because I looked at that and I looked at the differences" (S.V)	Waving gestures above the computer device that do not indicate any specific strategy (G.V)
Other	Any strategy not listed above	"And here is like half of it. But so and two halves make a whole" (S.O)	Using the hand to form a straight line through the middle of the whole shape to represent the line of symmetry (G.O)

- User 4, Shape P2, Session 1

Excerpt 3

> "Well it's based on the points, so the shape has 6 points, so needed 5 towers for the 6 points... because of how to works you get one point there, you go down, then another point, then you go over, on the same kind of layer... and then in the middle, so you don't just have a flat square, and you're pulling it up, you get two points, so it is pulling the whole thing."

Gesture: (pulls "up" with hands, points to towers, makes flat hand for layers)

Codes: S.PW, S.PF, S.M, S.O, G.PF, G.O, G.M

- User 11, Shape CH1, Session 1

Excerpt 4

> "Because the lines are the same way, as, the, uh, that shape."

Gesture: (shrugs)

Codes: S.V, G.V

- User 8, Shape P2, Session 1

Excerpt 5

> "By taking each point, each side, and creating it into a point on the graph" "on this shape, uh, this is about, uh 3 points wide, and 2 points tall, like, on this, and then also, like 2 points out."

Gesture: (at 'like this' points to two lights on the device one after the other.)

Codes: S.O, S.PF, G.PF

- User 7, Shape T2, Session 1

Excerpt 6

> "If it was hull then I knew it would automatically connect and fill in between the points, so all I really needed to do was make two triangles, and it would fill in the rest"

Gesture: (gestures with hands to indicate two parts moving together)

Codes: S.O, S.PF, G.M, G.PF

- User 11, Shape CH1, Session 2

Excerpt 7

> "Because, it didn't look like a pyramid, but like a right pyramid... like a right angle, one side is a right... I put four there, in each corner... I put one on top because it was the point, a vertex... and then I looked at the laptop and it looked like the shape."

Gesture: (points to different corners of the shape)

Codes: S.PW, S.PF, S.O, G.PF, G.V

- User 17, Shape CH4, Session 2

Excerpt 8

> "When I was trying to make this part, I was trying to make it small, from the middle... I made it look like it's supposed to look, I made it down, straight, up, right, down, straight, up... so I try to just mimic the shape and see how it works."

Gesture: (gestures along the path on the device that the user is describing)

Codes: S.PF, S.PW, S.M, G.M, G.PF

- User 1, Shape T3, Session 2

Excerpt 9

> "There's two U's, and um, like an entrance to a doorway."

Gesture: (traces with finger along different parts of the shape)

Codes: S.PF, S.O, G.PF

- User 5, Shape T3, Session 1

Excerpt 10

> "Basically drawing it out with my mind."

Gesture: (makes drawing motion with hand, then a sort of vague waving motion)

Codes: S.O, S.V, G.M, G.V

- User 2, Shape P3, Session 2