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Automating stem learning by engaging in artful-inspired play

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I dedicate this thesis to my husband, Eric.

If anyone is looking for us, we'll be at the Tomorrowland popcorn cart celebrating.

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ABSTRACT

Roth, Katie E. M.S.M.E., Purdue University, August 2016. Automating STEM Learning by Engaging in Artful-Inspired Play. Major Professor: Karthik Ramani, School of Mechanical Engineering.

A full range of experimental methodologies split between two distinct yet related projects was performed in an effort to define ways to automate STEM learning in artful-inspired play. Both projects aim to offer impactful learning experiences through artful-inspired activities meant to automate STEM (science, technology, engineering, mathematics) learning in children that are both scientifically and non-scientifically inclined. By participating in play that is both fun and engaging, learning is a byproduct of the activity which acts to automatically embed STEM knowledge and experiences within the user. Bridging the gap between STEM and artistic tendencies has the potential to provide a multi-faceted learning experience that could attract non-traditional STEM candidates, such as children with a passion for drawing. The first project presents the concept and initial prototype of a color-driven tangible learning environment that teaches mathematics, while the second project presents the preliminary results of longitudinal study conducted to analyze how children use hand-drawn sketching to expand and facilitate their design thinking for STEM-based activities.

The Math Bright Blocks introduce a gaming module that intends to cognitively color code mathematical operations and automate STEM learning by achieving increased

interest, cognitive speed, and excitement in children with regards to the field of mathematics. Conception, design, construction, and initial testing of the module were performed to innovate a new cross-cutting approach to education. However, through careful consideration, it was determined that the color space is too much of an unexplored arena and that additional theoretical frameworks and testing approaches are necessary for constructing an appropriate testing environment for color and its implications for children.

Lastly, the ways children use sketching methods to communicate design ideas during a variety of activities in the Purdue sponsored GERI *Toy Design Lab in Mechanical Engineering*, including how color is utilized to communicate ideas, were evaluated. The activities that this observational research focuses on are those that purposefully implemented hand sketching; Marshmallow Tower, Sketching Workshop, and the NERF Blaster challenge. With only 17 participants, there are not enough data points to be able to offer any type of meaningful statistical significance. Therefore, this work acts to establish a foundation built upon initial observation on which future in-depth sketching analyses can be facilitated. Observations of the participants offered mixed results. The participants did not use sketching for iterative design, but suggested in the respective survey materials that sketching was important for design planning. Additionally, observations made during the NERF Blaster challenge suggest that children need a physical representation to visualize in order to be fully engaged in sketching for design. Color was rarely used to facilitate design communication, and when used, colors were seemingly chosen based on real-world representations.

PART 1. MATH BRIGHT BLOCKS

The first project presents a theoretical tangible learning environment that utilizes color to teach mathematical concepts. Integrating digital components and microcontroller logic into the design makes it relevant to the current practices of the Maker Movement and meets the growing demand for exciting tech.

CHAPTER 1. INTRODUCTION

1.1 Motivation

There are many people that see themselves in a singular light; scientific or artistic. This gaming platform aims to bridge the gap between STEM and artistic tendencies by producing attractors for all types of users.

Color is an ever-present source of stimulation in children's lives. It exists in ordinary items, such as the colors of their toothbrush and toothpaste, to exciting items, such as the color scheme of their favorite toy collection. Being able to harness the power of color to teach STEM (science, technology, engineering, mathematics) methods is an interesting concept worth exploring.

1.2 Review of the Literature

1.2.1 STEM Learning

> " A consensus exists that improving science, technology, engineering, and mathematics (STEM) education throughout the Nation is a necessary, if not sufficient, condition for preserving our capacity for innovation and discovery and for ensuring U.S. economic strength and competitiveness in the international marketplace of the

21st century" (United States Congress and House, 2008). Studies show that the United States trails in performance in STEM learning to many other developed countries (Figures 1 and 2).

Grade 4		Grade 8	
Education system	Average score	Education system	Average score
TIMSS scale average	500	TIMSS scale average	500
Singapore[1]	606 ▲	Korea, Rep. of	613 ▲
Korea, Rep. of	605 ▲	Singapore[1]	611 ▲
Hong Kong-CHN[1]	602 ▲	*Chinese Taipei-CHN*	609 ▲
Chinese Taipei-CHN	591 ▲	*Hong Kong-CHN*	586 ▲
Japan	585 ▲	Japan	570 ▲
Northern Ireland-GBR[2]	562 ▲	Russian Federation[1]	539 ▲
Belgium (Flemish)-BEL	549 ▲	Israel[2]	516
Finland	545	Finland	514
England-GBR	542	**United States[1]**	**509**
Russian Federation	542	*England-GBR*[3]	507
United States[1]	**541**	Hungary	505
Netherlands[2]	540	Australia	505
Denmark[1]	537	Slovenia	505
Lithuania[1,3]	534 ▼	Lithuania[4]	502
Portugal	532 ▼	Italy	498 ▼

Figure 1. International average mathematics scores of 4th and 8th grade students (National Center for Education Statistics, 2011).

Grade 4		Grade 8	
Education system	Average score	Education system	Average score
TIMSS scale average	500	TIMSS scale average	500
Korea, Rep. of	587 ▲	Singapore1	590 ▲
Singapore[1]	583 ▲	*Chinese Taipei-CHN*	564 ▲
Finland	570 ▲	Korea, Rep. of	560 ▲
Japan	559 ▲	Japan	558 ▲
Russian Federation	552 ▲	Finland	552 ▲
Chinese Taipei-CHN	552 ▲	Slovenia	543 ▲
United States[1]	**544**	Russian Federation1	542 ▲
Czech Republic	536 ▼	*Hong Kong-CHN*	535 ▲
Hong Kong-CHN[1]	535 ▼	*England-GBR2*	533
Hungary	534 ▼	**United States1**	**525**
Sweden	533 ▼	Hungary	522
Slovak Republic	532 ▼	Australia	519
Austria	532 ▼	Israel3	516
Netherlands[2]	531 ▼	Lithuania4	514 ▼
England-GBR	529 ▼	New Zealand	512 ▼

Figure 2. International average science scores of 4th and 8th grade students (National Center for Education Statistics, 2011).

Additionally, the United States ranks low in the number of students that graduate with science and engineering degrees (Figure 3).

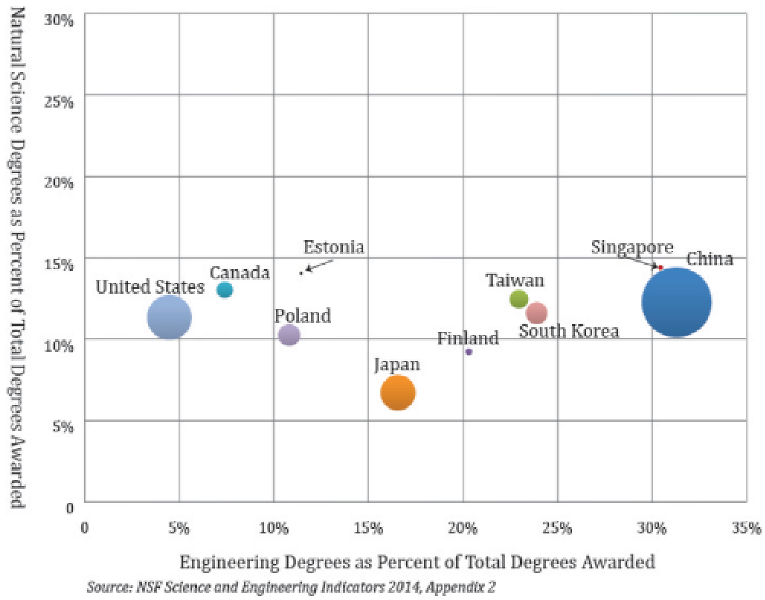

Figure 3. Engineering and Science Degrees Awarded by Country (2010) (Kraemer and Craw, 2014).

There is clear evidence for the need to strengthen "STEM education in the United States to ensure that the Nation's workforce can compete globally in high-tech, high-value industries" (United States Congress and House, 2008).

According to the National Research Council, mathematical proficiency has five interwoven and independent strands; understanding, computing, applying, reasoning, and engaging (National Research Council Staff et al., 2002). They are as follows:

- "Understanding: comprehending mathematical concepts, operations, and relations-knowing what mathematical symbols, diagrams, and procedures mean.
- Computing: carrying out mathematical procedures, such as adding, subtracting, multiplying, and dividing numbers flexibily, accurately, efficiently, and appropriately.

- Applying: being able to formulate problems mathematically and to devise strategies for solving them using concepts and procedures appropriately.
- Reasoning: using logic to explain and justify a solution to a problem or to extend from something known to something not yet know.
- Engaging: seeing mathematics as sensible, useful, and doable- if you work at it- and being willing to do the work" (National Research Council Staff et al., 2002).

The National Research Council suggests that when mathematics is taught according to the interwoven strands method, learning will be "more effective and enduring" and the need to repeatedly cover the same material will be eliminated (National Research Council Staff et al., 2002). Important to this gaming module, Moomaw (Moomaw, 2013) maintains that mathematical operations important for STEM education for young children include: "quantifying small amounts, comparing sets of objects (more, less, or equal), counting, ordering numbers (first, second, last, and so on), combining sets (early addition), taking away from sets (early subtraction), dividing materials among friends (early division), and understanding patterns and relationships" through activities such as sorting.

In Design Make Play: Growing the Next Generation of STEM Innovators, Honey and Kanter are confident that presenting STEM as "creative, hands-on, and passionate endeavors" will attract young people to science and technology (Honey and Kanter, 2013). One way to do this is through play, which can "foster important learning skills in science, technology, engineering, and math (STEM) as well as in literacy and the arts" (Honey and Kanter, 2013). Maltese, Melki, Wiebke (Maltese, 2014) found that there is no clear life pathway responsible for triggering interest in STEM education; however, the majority of the participants in their study became interested in grade 6 which "suggests that early experiences are critical for recruiting students to STEM fields." Among the experiences that garner initial interest, they found that mathematics and logic games were prominent (Maltese, 2014). Regardless of the learning activity, children must receive support from their adults, namely parents and teachers, if they are to succeed in establishing a strong STEM foundation (Maltese, 2014; Moomaw, 2013; United States Congress and House, 2008).

1.2.2 Constructionism and the Maker Movement

"The Maker Movement refers broadly to the growing number of people who are engaged in the creative production of artifacts in their daily lives and who find physical and digital forums to share their processes and products with others" (Halverson and Sheridan, 2014). The notion of learning though play is a foundational concept of the Maker Movement, which research suggests is where "innovation and creativity will be found" (Honey and Kanter, 2013). Unlike the typical school setting, failures are not discouraged because all experiences, both successes and failures, are seen as learning opportunities (Honey and Kanter, 2013). Iterating ideas to reach a solution is an important part of growing the curious and abstract mind. Similar in thinking is the tinkering approach where immediate feedback to design input, free thinking, idea exploration, and continuous experimentation are encouraged and necessary (Honey and Kanter, 2013). For the proposed gaming module discussed herein, immediate feedback is of particular importance because the users need to be able to see the results of their inputs so that they can adjust their thinking to define new solutions.

The Maker Movement is tied to the Piaget-led belief of constructionism (Piaget, 1954), where knowledge is constructed through hands-on experiences and the resulting mental actions (State University of New York Early Childhood and Training Program, 2016) when the learner is involved in meaningful activities (Martinez and Stager, 2013). Using mental actions to organize thoughts (schemas), children are able to form assimilations to existing knowledge or accommodations to new knowledge from any information that they come across (State University of New York Early Childhood and Training Program, 2016). The State University of New York Early Childhood and Training Program (State University of New York Early Childhood and Training Program, 2016) reiterated that these schemas are crucial to the cognitive development of children and as they become more complex , allow movement through the four different periods of knowledge construction. During the sensorimotor period (birth to age 2), infants and toddlers use their senses and fine motor skills to construct knowledge on their environments. The preoperational period (ages 2 to 7), requires lots of hands-on activities available to children for learning. During the concrete operations period (ages 7 to 11), "children can perform more complex mental operations" (State University of New York Early Childhood and Training Program, 2016). Finally, children are able to have abstract thoughts during the formal operations period (ages 11 to 15). Games are seen as being a facilitator of constructionism because of the active learning environment that they encourage (Li et al., 2013). This game platform is interested in the theoretical construction of mathematical knowledge and expertise as the game progresses.

Much research has been performed around the notion that games serve as a learning environment. Li, Cheng, and Liu saw that games "promoted the learning experience by either reducing the challenge perception or promoting skill perception" and engaged a variety of students in active learning activities (Li et al., 2013). As it is with the rest of the human race, children are more acceptable to new experiences and challenges if they think they are having fun which makes games, a well-known method of play for children, a ripe environment for learning. In *Game Mechanics: Advanced Game Designs*, Adams and Dormans defined a set of core game mechanics and the associated game-based learning (Adams and Dormans, 2012), see Table 1.

Table 1. Core game mechanics and associated constructivist learning adapted by Dickey (Dickey, 2015) from (Adams and Dormans, 2012).

Core Mechanic	Constructivist Learning
Physics mechanics	Experiential
Internal economies mechanics	Resources
Progression mechanics	Scaffolding
Tactical mechanics	Inscription
Social mechanics	Discourse tools

Their framework suggests that, by engaging in meaningful play afforded by games, constructivist learning takes place inside the learner's head. Dickey (Dickey, 2015) further investigated the notion of games as constructivist learning environments by developing a set of secondary game mechanics and the types of knowledge according to Bloom's Taxonomy that they elicit, see Table 2.

Table 2. Secondary game mechanics and associated knowledge (Dickey, 2015).

Mechanics	Summary and Genre	Objectives	
		Bloom's Taxonomy (1956)	
Collection mechanics	This mechanic concerns the gathering or collecting of a specified number of objects (points, bounty, territory, etc.) Game genres: action, role-playing, simulation, and strategy games	Knowledge Comprehension	Remembering Understanding
Elimination mechanics	This mechanic requires players to defeat specified enemies, agents or Game genres: action, role-playing, simulation, and strategy games	Knowledge Comprehension	Remembering Understanding
Avoidance mechanics	The mechanic requires players to avoid losing objects or territories. Game genres: action, role-playing, simulation, and strategy games	Knowledge Comprehension	Remembering Understanding
Race mechanics	This mechanic requires players to beat an opponent(s) in some type of race negotiating space, time or both.	Knowledge Comprehension	Remembering Understanding
Resource management mechanics	This mechanic requires players to balance and negotiate resources (e.g., tokens, money, health, character attributes and traits) to achieve one or Game genres: action, role-playing, simulation, and strategy games	Knowledge Comprehension Application Analysis Synthesis Evaluation	Remembering Understanding Applying Analyzing Evaluating Creating
Construction mechanics	This mechanic requires players to build, construct and/or alter an Game genres: action, role-playing, simulation, and strategy games	Knowledge Comprehension Application Analysis Synthesis Evaluation	Remembering Understanding Applying Analyzing Evaluating Creating

Tying back to the notion of mental tinkering for learning, Kiili (Kiili, 2005) argued that for engaging and seamless learning, "games must be designed based on a clear and challenging problem, and must provide facilities for students to reflectively observe the outcomes of actions performed to solve the problem." While the games presented here were typically internet or other types of electronic games, the basic foundational principles of learning through game play apply to all types of games.

Adult interaction is important for constructionist learning. Using toys such as blocks and puzzles in free-play has been shown to promote spatial thinking (Ginsburg, 2006; Ginsburg, 2008; Honey and Kanter, 2013; Levine, 2012; Newcombe, 2010; Wolfgang, 2001). "Adults may facilitate children's learning by gently scaffolding their discoveries using a variety of techniques, including commenting on children's insights, co-playing with them, asking open-ended questions, suggesting ways to explore and play with the materials in ways that children might not have thought to do, or creating games that help them hone their knowledge and skills" (Cross et al., 2009; Honey and Kanter, 2013). In guided play environments, adults set up play activities that are "intended to provide experiences related to curricular content learning opportunities" (Honey and Kanter, 2013) which studies have shown result in a higher probability of learning than in a free play environment (Fisher et al., 2012; Miller and Almon, 2009; Resnick et al., 2007; Youell, 2008). This suggests that guided play games are valuable learning tools that should be made available to educators and all other invested parties to promote learning.

1.2.3 Tangible Digital Learning

Embedding digital components into tangible interfaces has been shown to "support traditional exploratory play" because of the extended interactivity that they can offer (Revelle et al., 2005). Research suggest that "tangible environments offer the potential to exploit pertinent features of both physical and virtual environments" (Price and Falcão, 2009); however, learning metaphors and the representative associations need to be carefully considered for the intended audience (Price and Falcão, 2009). One solution to this is to make the learning object as engaging and enjoyable as possible. Rooted in these interactive surfaces is the notion of edutainment, which is the combined traits of educational and entertaining activities meant to "increase engagement, emotion, and motivation" (Sorathia and Servidio, 2012). An ideal platform for edutainment, games allow freedom to learn through play by coupling with inherent physical manipulation with action validation to devise strategies (Pillias et al., 2014).

1.2.3.1 Related Work

There have already been great strides in presenting digital toys that are activated through tactile interaction. Similar to this proposed design, the Learning Cube (Terrenghi et al, 2006) utilizes a cube shape with a digital screen on each face that displays questions or answers in either text or images. Similar to this project, the cube shape was selected because it is a known shape and manipulative recognized by young children and adults. Shaking, throwing, and rotating were the prescribed inputs used to gain engagement. By experimenting with simple math games with kids in the age range of 7-12, Terrenghi, Kranz, Holleis found that " distracting children from the learning task as conventionally presented and engaging them in a quiz game that they can play with others motivates them and challenges their skills" (Terrenghi et al, 2006). A key difference between the Learning Cube and Math Bright Blocks is that the latter is motivated to educate through color stimuli.

1.2.4 Target Audience

Both mathematical experience and dexterity were considered to determine the target age range for the game. Personal interviews with educators of young children (Appendix A) suggested that ages 4-6 are the best candidates for this platform because that is the age range that they begin learning mathematical concepts, such as addition, subtraction, and "memorizing numbers up to 20" (see Appendix A.2 Question 1). Very young children have limited control over their fine motor abilities (Revelle et al., 2005); however, by Kindergarten children have improved dexterity and are able to firmly grasp and transfer objects, (see Appendix A). "Physical objects have been traditionally used in kindergarten and elementary schools to introduce young learners to abstract concepts such as quantity, numbers, base ten, fractions, etc." (Zuckerman et al., 2005). Therefore, the target age range for the initial game module is 4-6.

1.2.5 Color

There exists several studies on the cognitive connection of perception to color. Zeimbekis (Zeimbekis, 2013) argued that "perceptual experience is cognitively penetrable", and more generally, that people make choices based on their pre-determined associations with color. An example of this is always associating a heart with the color red or a banana with yellow. Similarly, Mehta and Zhu (Mehta and Zhu, 2009) claimed that "when people repeatedly encounter situations where different colors are accompanied by particular experiences and/or concepts, they form specific associations to colors." These studies support Carl Jung's theory of collective unconscious, associations such as with color, are pre-programmed (Jung et al., 1969). Hsu, Kraemer, Oliver, Schlichting, Thompson-Schill performed a pair of studies that "demonstrated the first neuroimaging evidence that context (a task factor) and cognitive style (an individual factor) can influence color knowledge retrieval, and it may be that these factors also influence the degree to which color knowledge retrieval and color perception share a common neural substrate" which suggested that " the degree of overlap between color retrieval and color perception depends on the match between the resolution of the information required of each" (Hsu, 2011). The Math Bright Blocks aim to use these notions by cognitively coding colors to mathematical operations.

A fascinating study by Mehta and Zhu in *Blue or Red? Exploring the Effect of Color on Cognitive Task Performances* used the concept of achievement motivation theory and postulated that "different colors enhance different achievement motivations, which can then affect the performance on different types of cognitive tasks" (Mehta and Zhu, 2009). Similarly, Elliot and Maier defined six premises that must be met "for color to effect the performance of cognitive tasks" (Elliot and Maier, 2007). Olsen summarized them in *Effect of Color on Conscious and Unconscious Cognition*; "color should be able to carry a specific meaning", "the meaning of colors is based both on learned associations and on biological responses", "the perception of color alone will cause evaluative processes", "these evaluative behaviors influence motivated behavior", "the influence of psychological functioning is implicit and automatic", "and the meaning and effects of color are based on context" (Olsen, 2010). In her experiments, however, Olsen was unable to produce results similar to those in (Mehta and Zhu, 2009) and (Elliot and Maier, 2007). She questioned whether the tests or the setting of the experiments were unable to invoke an achievement setting for the participants, thereby unable to replicate the results of previous studies. This suggests that careful planning of the testing environment for color evaluation is critical. Her work did support the idea that the "probability of recollection decreases when an individual's attention is divided" (Olsen, 2010). Therefore, for the purpose of this project, developing an attention-grabbing game was crucial for color associations and math memory retention.

The benefits of color should not be limited to expressive outlets for artwork, but expanded to the world of education and learning. There have been several studies into the influence of color in education. As early as 1957, color was seen as a valuable tool for teaching mathematics (Science, 1957). Color televisions were used to offer lectures in mathematics to groups of in-service high school math and science teachers. Color kinescopes of the televised lectures provided an "opportunity for comparison of various techniques" and were "essential to evaluation of the experiment" (Science, 1957). In a study by Van Houtem and Rolider, color was used to " facilitate the acquisition of labeling tasks in learning disabled students" by way of mediated transfer process (Van Houten and Rolider, 1990). They observed rapid learning in all students after the introduction of a color mediation procedure, such as the "association of each numeral with a color" (Van Houten and Rolider, 1990). Engelbrecht examined a "compilation of studies conducted by color psychologist, medical, and design professionals" to highlight a connection between color and its " ability to enhance our experience of the learning environment" (Engelbrecht, 2003). Though, she was primarily evaluating the external influence of the colors of the learning environments themselves, such as color of the walls in a classroom and the resulting effects on the students.

Additionally, there have been numerous studies that evaluate the emotional associations that children have with color, such as those done by Boyatzis & Varghese (Boyatzis and Varghese, 1994). This project, however, is not concerned with the emotional associations that children have with colors since a goal is to form associations between color and mathematical operations. Obviously, emotional responses will be considered, but they will be associated with the overall game module and not specifically with the individual colors in the game.

1.3 Project Overview

Current research suggests a need for increased attention to STEM education for children. Engaging them at an early age and making the subject matter seem fun, innocent, and enjoyable is a great way to build the foundations in their learning with the hope that they will continue to build on the knowledge they gain. The objective of this project was to develop a tangible learning device that makes learning math fun and appealing to children. A well-known toy, the block, was used as a basis for the external design used to house the components. Integrating digital components into the design makes it appealing in the modern day sense of gaming and electronic toys. Using RFduino technology as the primary logic communicator, it is intended that the user be able to select different games to play within a single set of blocks. This makes it possible to have an unlimited number of games that could be played on a single set of blocks. Carefully crafting the games so that they could be played individually or with a parent or teacher reinforces explorative learning and guided play. An interesting approach to learning and attracting attention, this gaming module attempts to code colors to mathematical operations. By doing so, this color-driven play space hopes to automate STEM learning by achieving increased interest, cognitive speed, and excitement in children with regards to the field of mathematics.

CHAPTER 2. INITIAL PROTOTYPE

2.1 Introduction

This chapter details the prototyping activities undergone for the Math Bright Blocks. Information is provided for the electronic (internal) components as well as the design and construction of an exterior shell to house the components. Prototyped and intended games are discussed along with the considerations for future additions and optimizations that can and should be implemented for further enhancement.

2.2 Internal Components

The following components (shown in Figure 4) were used to facilitate the intended actions proposed by the games in the initial prototype: RGB LED matrix panel (item 1), battery, Bluetooth 4.0 low energy RFduino microcontroller kit (items 2 and 3), RGB LED shield (item 4), and battery shield (item 5).

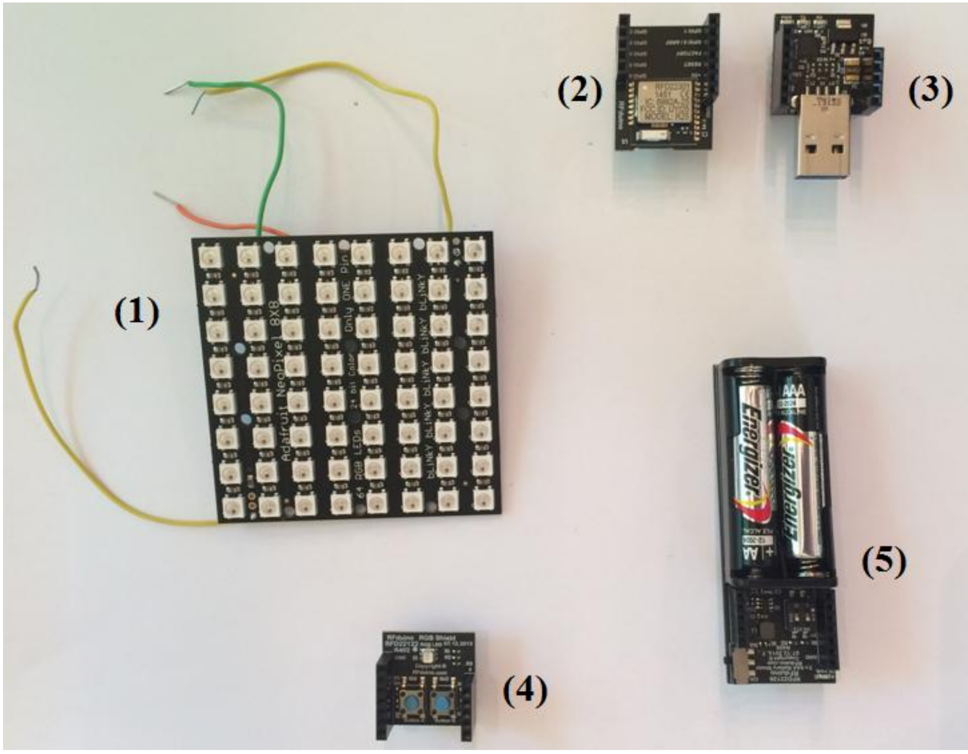

Figure 4. Internal block common components.

Items 2-5 are stock RFduino parts; they were not manipulated for the purposes of this project. Item 1; however, did need to be modified to meet the needs of the users.

The lit matrix panel contains 64 LED lights arranged in an 8x8 grid. The target age range of 4-6 years old coupled with their ability to only be able to memorize up to 20 (see Appendix A.2 Question 1), required that the number of LEDs visible to the users be manipulated. To do so, in conjuncture with simple programming, a simple arrangement of black cardstock and wax paper was utilized to reduce the grid from 8x8 to 4x4, making 16 the highest number possible. Holes were cut on the cardstock that equated four lights to one when layered with the opaque wax paper, (see Figure 5).

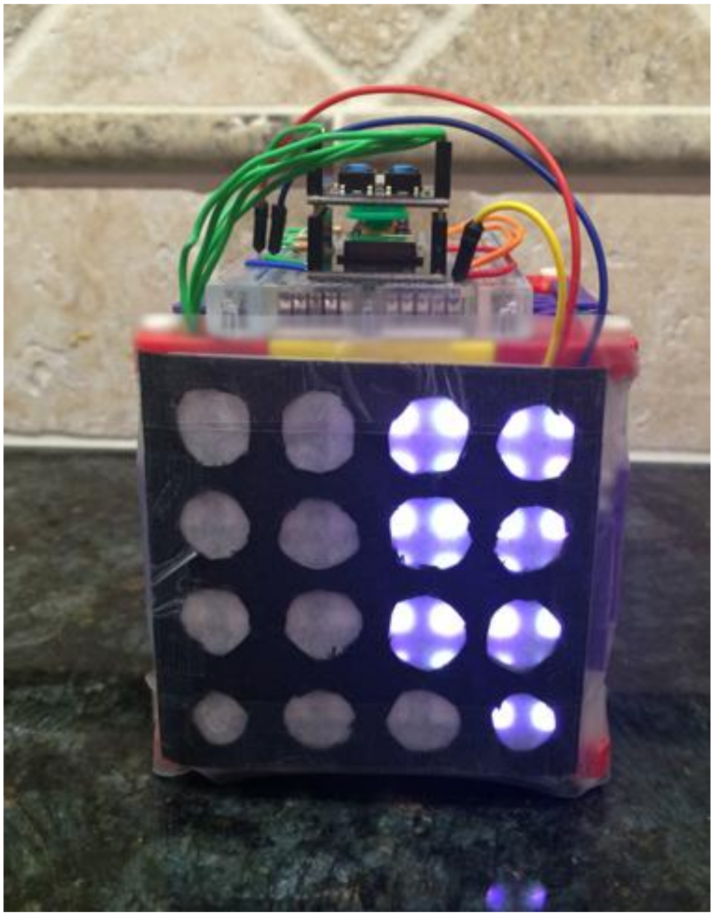

Figure 5. Black LED matrix topper.

Manual push buttons were used in conjuncture with a breadboard attached to the outside of the host block's external shell (Figure 6) to offer a response input source for the users. Once more advanced logic programming can be attained, force sensitive resistors will be embedded to form a more interactive link for the tangible user interface.

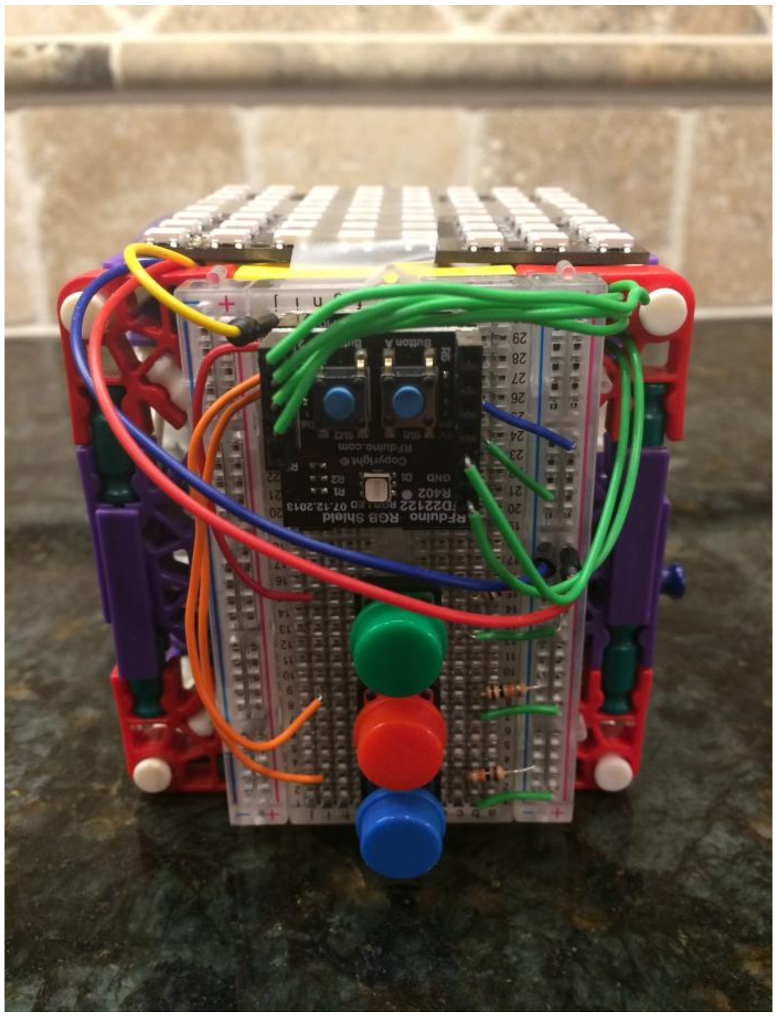

Figure 6. Host block answer selection components.

2.3 Exterior Shell

The overall size of the initial prototype was determined and controlled by the stock components (purchased from stores including Adafruit and Micro Center) used to construct it. Adjusting perfectly to the largest component, the LED panel, K'NEX toy parts were used to construct a hard outer shell (Figure 7). This shell protects the internal components and solidifies the block shape the project required.

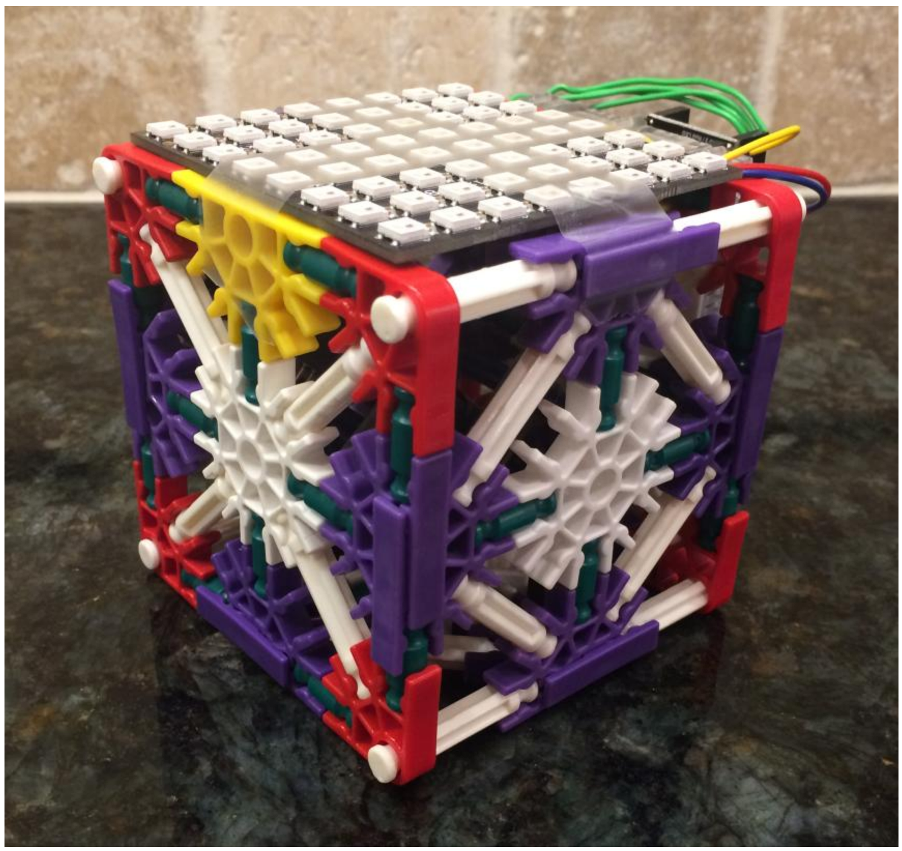

Figure 7. Exterior shell built from K'NEX pieces.

CHAPTER 3. GAME DESIGN

3.1 Introduction

Using RFduino logic, the initial prototype was designed to have a host block and two slave blocks. An important design goal for this project was to develop a single toy on which an indefinite number of games could be played. All games have been designed, or intended, to provide immediate feedback of the user's performance. Games developed here have been proven to build mathematical reasoning in younger children (Moomaw, 2013).

3.2 Prototyped Games

Presented in this section are the games that were successfully programmed for the initial prototype.

3.2.1 Addition Subtraction

This game is intended to be presented with limited instructions to the child since the concepts should be grasped through iteration and play. Three blocks are required for the Addition and Subtraction game which is based around the simple formula noted in Equation (3.1).

$$x \pm y = z \tag{3.1}$$

This game was designed so that block 'x' is always the first number in the equation. In other words, block 'y' is never the initial number in the problem. To help alleviate any confusion, the game was programmed such that block 'x' is always blue which lets the user know which number that they will either be adding to or subtracting from. Block 'y' varies between green that is coded to addition (Figure 8) or red that is coded to subtraction (Figure 9).

Figure 8. Blocks during addition question.

Figure 9. Blocks during subtraction question.

By color coding the mathematical operator, it decreases the number of required blocks and attempts to form color associations to mathematics. The LEDs on the cube face illuminate in a randomized pattern with the goal of adding spatial awareness and quick thinking. Once both the 'x' and 'y' blocks are illuminated, the child interfaces with the answer block to answer the problem before them. It was difficult to integrate force sensitive resistors into the working prototype, so manual push buttons were integrated for the answer block. The green button adds quantity 1, red button subtracts quantity 1, and the blue button submits the answer. The user is able to visually see their answer illuminated in white LEDs on the answer block. If an incorrect answer is submitted, the answer block changes from white to red (Figure 10).

Figure 10. Red host block indicates incorrect answer submitted.

If a correct answer is submitted, the answer blocks displays a rainbow pattern (Figure 11).

Figure 11. Rainbow host block indicates correct answer submitted.

The user is able to submit responses to the question until the correct answer is achieved. The game resets to a different problem each time a correct answer is submitted.

3.2.2 Multiplication and Division

As it is with the Addition and Subtraction game, three blocks are required here with Equation (3.2) being the embedded formula to be learned by the user.

$$x \frac{\times}{\div} y = z \tag{3.2}$$

When programming this game, additional care had to be taken to ensure that all solutions were whole numbers. To differentiate from the Addition and Subtraction game, block 'y' is either yellow which is coded to multiplication (Figure 12) or purple that is coded to division (Figure 13).

Figure 12. Blocks during multiplication question.

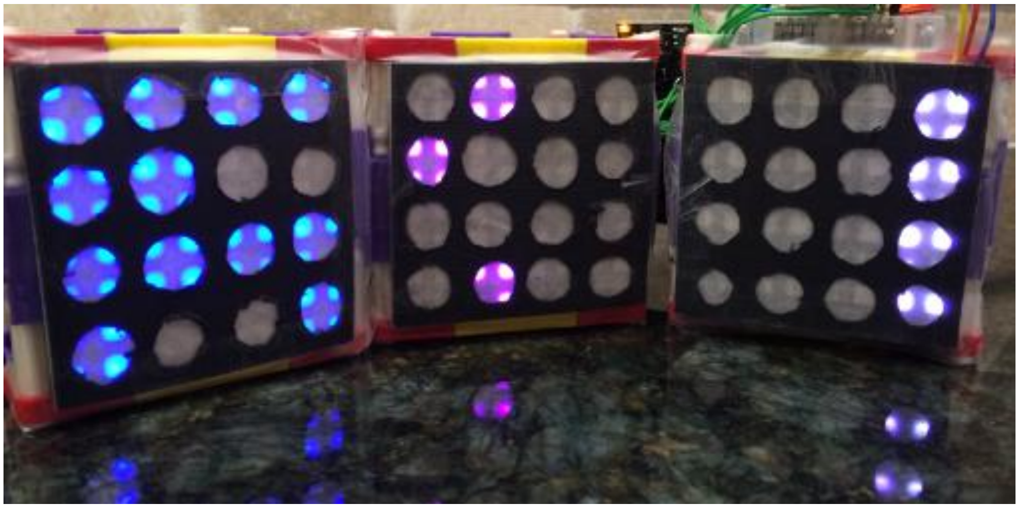

Figure 13. Blocks during division question.

Block 'x' is kept a continuous blue to reinforce the concept of appropriating the initial number in the problem. All other logic and required actions are the same here as they are in the Addition and Subtraction game.

Currently, both the Addition and Subtraction and Multiplication and Division games appear simultaneously on the initial prototype. Without the iPad interface in place, it was impossible to be able to select a different game to play. Therefore, both are combined at this time. However, any confusion as for how to proceed should be alleviated with the color coding that has been embedded into the mathematical operators.

3.3 Intended Games

Multiple game concepts were developed for the Math Bright blocks; however, due to programming knowledge and experience constraints, it was difficult to successfully launch all of them. This "Intended Games" section presents the games that were either too difficult to facilitate or program with current knowledge.

3.3.1 Sorting

For the Sorting game, a larger quantity (ten or more) blocks is required to play. Once the game has been initiated, each of the blocks will illuminate in a different color, i.e. red, blue, green, purple, etc. as in Figure 14.

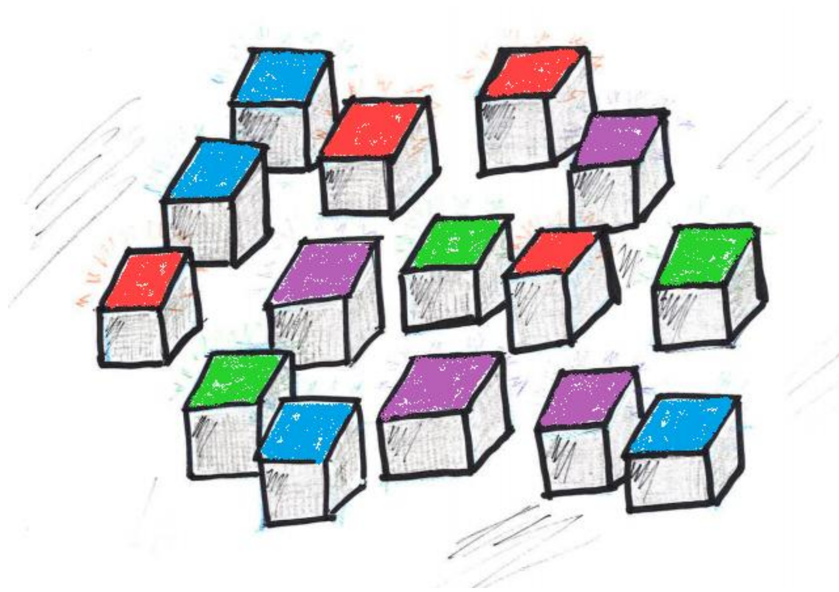

Figure 14. Arrangement of randomly illuminated blocks in sorting game.

The goal of the game is then to sort all of their blocks into their respective color groups. For example: all blue blocks are grouped together, all red blocks are grouped together, and so on. Once a color is correctly sorted, that entire color group will illuminate with rainbow colors and vibrate before returning back to its original color for continued sorting. This is illustrated in Figure 15, which shows all of the 'red' blocks from Figure 14 illuminating in rainbow since they have been correctly sorted.

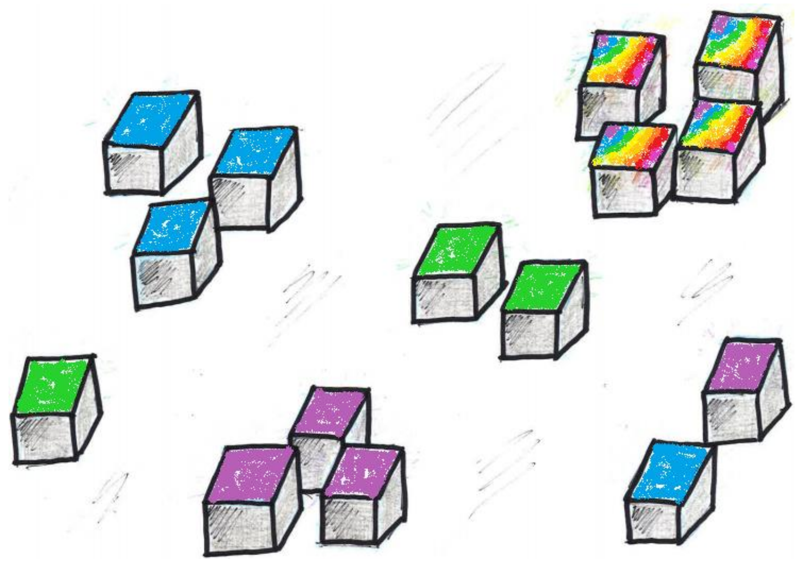

Figure 15. Sorted blocks - the red blocks from Figure 14 have all been sorted correctly and the rainbow feedback has been initiated.

This cheerful feedback is a positive reinforcement style mechanism intended to get the child even more excited to continue the exercise (see Appendix A). An incorrect sorting action would result in a single vibration with no accompanying illumination.

3.3.2 Memory

The Memory game is intended to be near identical to the logic of the sorting game. Users will still have to sort the blocks according to color. The only difference here is that the blocks' lights will turn off after a certain amount of time which prompts the users to sort the blocks into color groups based on memory. The challenge and difficulty of this game could be altered by adjusting the time and/or frequency that the lights remain illuminated.

3.3.3 Ordering and Sequencing

The purpose of the Ordering and Sequencing game is to build a fundamental understanding of how numbers progress in sequence and to get a sense of progression. The method of participation is quite simple; a group of blocks illuminate with a different number of LEDs on each one and the user then has to arrange them from smallest to largest as is shown in Figure 16.

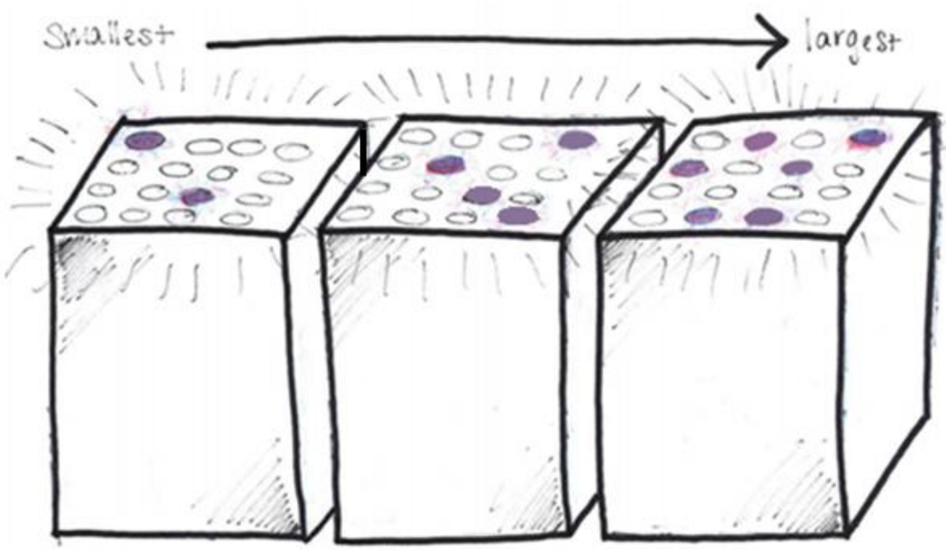

Figure 16. Sequencing Game Dramatization.

The feedback is similar to those of other games. When a correct sequence is arranged, the correctly aligned blocks blink through a rainbow color scheme and vibrate. When an incorrect sequence is arranged, a single vibration is triggered.

3.3.4 Counting

The Counting game is intended to be interactive between a child and their parent or teacher. The child will have an answer block and a set of blocks scattered in front of them while the parent or teacher has the 'master' component (which is intended to be an iPad). Once the game is initiated, the blocks in front of the child will illuminate randomly and the teacher or parent is prompted by the iPad to verbally ask a question that references the set of scattered blocks, such as "How many purple blocks are there?". The child then uses the designated answer block to input their response. Depending on the response, the answer block will illuminate rainbow and vibrate if correct and vibrate once with no added effects if incorrect. The iPad receives feedback for the answers and the teacher/parent is then able to prompt the blocks to change for the next question.

3.3.5 Abacus

Also intended to be interactive, the Abacus game should be used between a child and a parent or teacher; however, it requires some initial setup from the parent/teacher and some pre-existing knowledge of the child for abacus methodologies. For this game, a minimum of 7 blocks is required; two blocks each worth a value of 5 and five blocks each worth a value of 1. The set of two blocks would be a different color than the set of five blocks, such as red and blue. Prompted by the iPad, the teacher/parent would verbally say a command similar to "Show me 6 on the abacus." For the correct answer, the child would then interact with one each of the set of two (worth 5 each) and the set of five (worth 1 each) to equal the quantity 6 that they were prompted for. The same rainbow and vibration feedback also applies here.

CHAPTER 4. FUTURE ADDITIONS AND OPTIMIZATION

This chapter presents the intentions for broadening the game to a wider audience and making it even more accessible and user-friendly.

4.1 System Improvement

Further work needs to be done to implement a "smart" interface, such as through an iPad or other type of tablet. It is intended that once this digital construct is developed, that there will be a dashboard of sorts that the parents, teachers, or even children can use to easily select which game they would like to play. A mock-up of an example dashboard is show in Figure 17.

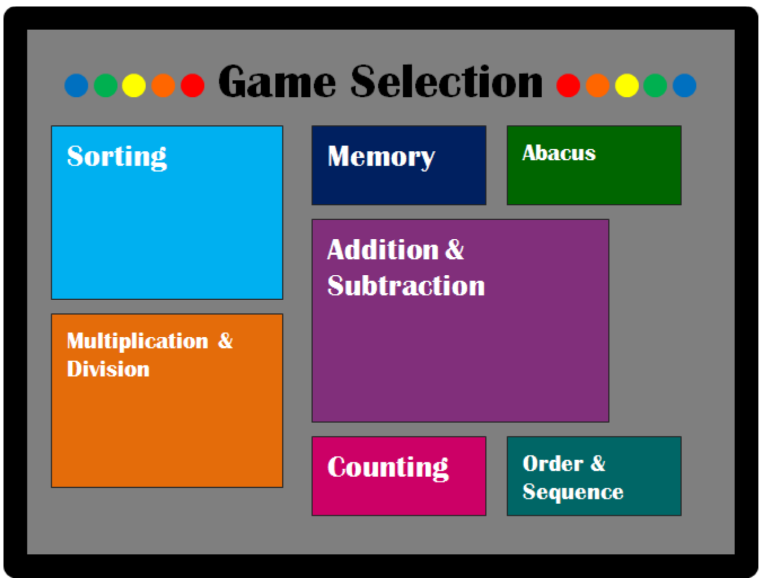

Figure 17. iPad game selection mock-up.

In addition to being able to easily choose which game to play, the tablet connection is also intended to provide a feedback bank so that parents or teachers are able to see the progress of the child as they use the blocks. Each set of blocks would need to be specially coded on a per child basis to make this work; however, the benefits would be great. If the child was able to use the same set of blocks at home and in the classroom, there could be a constant source of feedback on progress that the parents and teachers could monitor simultaneously. This would be useful for identifying tasks that the children excel and struggle with, which helps the facilitator prioritize which games to play more frequently.

Another potential classroom interactive option is to have a set of blocks for each student as the teacher has the iPad acting as the master component. If each set of blocks could be linked to the one master iPad, the teacher could get feedback on how every student in their class was performing.

4.2 User Customization

To make the games more personal to the user, there are a variety of options that could be implemented. One such option is including the ability to select a color palette for color blind individuals since they would not get the same benefits using the blocks in their current state. The most important features that could be implemented have the ability to add complexity and difficulty which could then be leveraged to use the blocks with even more age groups. Methods of doing so include adding a timer function that mandates a certain amount of time in which each challenge must be completed, increasing the total number range to be beyond 16, and using different types of identifiers to be sorted, such as shapes, even and odd numbers, and words for math word problems.

4.3 Game Expansions

Adding Bluetooth functionality to make the blocks aware of their relative locations would prevent the need for them to be physically connected for progression and grouping games. While this is mostly a logic-programming expansion, it would make the games much simpler to carry out because the user would not have to be concerned with logistics and could instead focus on fun. Additionally, there needs to be a method for tinkerers to be able to design and test their own games on the blocks, lending more to the digital side of the Maker Movement.

4.4 Physical Design Considerations

For future consideration, minimizing the size is important for making it more manageable for children. Currently, the larger size makes it clumsy and awkward to manipulate. Another way to make the blocks easier to handle and introduce a more tangible environment is to replace the current push buttons with the force sensitive resistors that were purchased for the initial prototype. Unfortunately, they were not able to be implemented due to the complexity of coding that was required which was disappointing since pushing on the resistors was intended to be the primary input source for the children's responses. Mini motor discs were identified as being an optimal way to introduce vibration as a feedback mechanism during game play. As with any consumer design, decreasing the overall power consumption is important and should be considered for future work. On a more general level, the number of interactive and illuminated surfaces need to be expanded.

CHAPTER 5. TESTING IN THE COLOR SPACE

It was difficult to determine how to define an appropriate environment for testing learning aptitude, retention, and improved subject matter interest based on color as the intended primary stimuli. When this project was first conceived, it was assumed that evaluating learning retention comparatively between color and black-and-white stimuli like other studies (Van Houten and Rolider, 1990) would be performed. However, intensive programming for test design is necessary for that to be possible. It was very difficult to carry this out for a solitary project. Collaboration with psychology experts that specialize in developmental child psychology is a necessary measure to be taken for any future endeavors.

CHAPTER 6. CONCLUSIONS

Through careful consideration, it was determined that the color space is too much of an unexplored arena and that additional theoretical frameworks and testing approaches are necessary for constructing an appropriate testing environment for color and its implications for children. Collaboration with cognitive and developmental psychology specialists, such as Dr. Elizabeth Spelke of Harvard University, is required to appropriately define the color space. Despite the lack of feedback in a child-based environment, this research opportunity offered a full cycled making experience of initial design, building, and testing. In support of previous work, an 'edutaining' tangible learning environment (Pillias et al., 2014) was designed to address the mathematical operations important for STEM education in younger children (Moomaw, 2013) while utilizing color coding (Hsu, 2011; Jung et al., 1969; Mehta and Zhu, 2009) for retention and engagement. The required time, effort, and knowledge-base was beyond the scope of a Master's project; however, the foundation has been set for expansion and exploration by future projects.

PART 2. SKETCHING IN STEM DESIGN

The second project analyzes the use of sketching by children during design activities. Unless otherwise stated, all images contained in this half were developed by and for the use of the C-Design Lab at Purdue University; permission was given for use.

CHAPTER 7. SKETCHING INTRODUCTION

7.1 Motivation

Sketching is an expression usually associated with artists and other creative-types. Potentially, it could be a method for creating interest in children that are not necessarily STEM-inclined to engage in such activities. Attracting different perspectives and skill sets to the STEM environment could lead to increased solution generation. Currently underutilized in education, sketching is an invaluable tool in all stages of the design process that could be a wonderful tool for children in mapping out their ideas in non-verbal ways. It is the hopes of the author that sketching could provide a bridge between science and art for a fully formed experience.

7.2 Review of the Literature

7.2.1 Mental Models

This study is considering how children use sketching during design and the associated mental imagery that contributes to the physical sketching. Observations by Cross and Cross (Cross and Cross, 1996), Gross (Gross, 1996), and Verstijnen, et al. (Verstijnen et al., 1998) promote that designers are encouraged to operate at a more abstract level through imagery and visual thinking. In 1991, Goldschmidt suggested that "sketches give access to various mental images - figural or conceptual, that may potentially trigger ideas that might be useful in solving the design problem at hand" (Goldschmidt, 1991) Similarly, Yang and Cham proposed that "understanding the role of sketching in design will provide insights for better design education and better interpretation of observable design activity in our quest to understand the design activities and cognitive processes that occur during the design process" (Yang and Cham, 2007). Yang also suggested that sketching is "a way to mentally offload concepts during complex design activity" (Yang, 2009). A probable scenario of mental offloading by children is when they are trying to explain something through verbal, gestural, or written communication.

7.2.2 Sketching for Design

There has been quite a bit of research done on sketching and its associations with design thinking. In "Observations on Concept Generation and Sketching in Engineering Design", Yang proposes that sketching is a fundamental element of design thinking, critical to generating concepts, and is a language for handling design ideas (Yang, 2009). Supporting these claims are the 1999 observations by Schrage that suggest that the success of a design is directly influenced through prototyping (Schrage, 2000), which often includes sketching. Ultimately, engaging students in "authentic design activities", such as sketching, is the best way to encourage design thinking (Martinez and Stager, 2013). This study hopes to witness the iterative design thinking process of children through various sketching enabled tasks.

Sketching is such a broad form that it can be subcategorized into different types. Ferguson identified three types of sketches and classified them in terms of their intended purpose; the thinking sketch is a reflective medium, perspective sketch is a design blueprint, and the talking sketch involves collaboration (Ferguson, 1992). Moving through the various types of sketches is part of an iterative process that encourages quick thinking and integration of art-based mediums into their accelerated learning (Martinez and Stager, 2013).

7.2.3 Collaboration

Shah, Vargas-Hernandez, Summers, and Kulkarni developed a collaborative sketching technique, called C-Sketch, that was used as an idea generation technique for engineering design and based on the " premise that sketching is important to design, collaboration of ideas provides diversity in design, and that provocative stimuli from other idea sketches may prove to be catalysts in developing creative new constructs" (Shah et al., 2001). In their study, they facilitated a group sketch activity by prescribing the way in which the sketch was shared. Within C-Sketch framework (Figure 18), the design was passed through the team and each person had the ability to change something with each iteration.

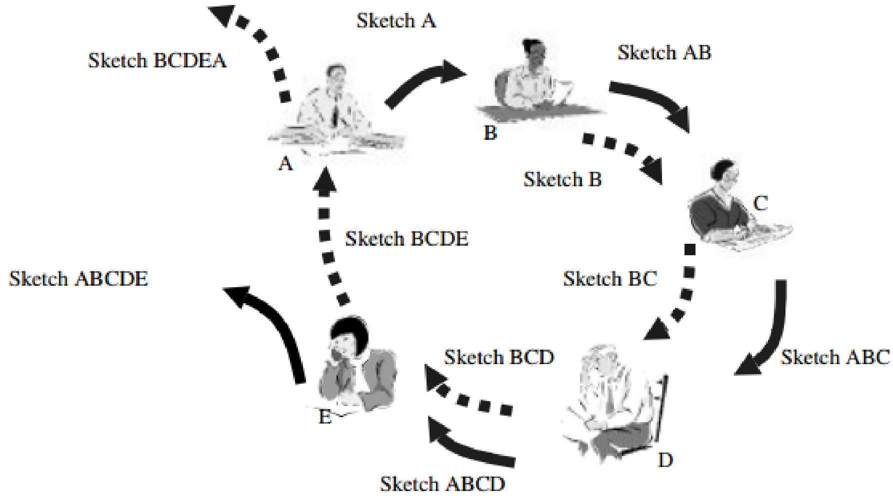

Figure 18. C-Sketch methodology image from (Shah et al., 2001).

At the conclusion of the exercise, there were a number of solutions equal to the number of participating designers. Their progressive idea generation method supported Goldschmidt's 1992 observation of serial sketching where new shapes and relationships among shapes are created as sketching progresses on paper that extend beyond what was intended at the design's beginning (Goldschmidt, 1992) Aiding in their claims are the observations by Carson and Carson (Carson and Carson, 1993), Kolodner and Wills (Kolodner, Wills, 1996), and Hirst (Hirst, 1992) that found that receiving design feedback appears to facilitate an enhanced design space. Group collaboration techniques during sketching are a part of this particular observational space.

7.2.4 Current Utilization in Primary and Secondary Education

At this time, there are limited studies into the effectiveness of utilizing sketching to facilitate learning in children. Most of the existing research focuses on individuals that are either already at university or the workplace, both primarily engineering. Those studies were not considered since no direct parallels could be drawn to this child-based study. The observations presented here should offer new insight into how sketching can and should be utilized with children.

7.2.5 Color in Sketching

At this time, there appear to be no research studies linking the use of color with the potential impact on prototyping design.

7.3 Project Overview

The purpose of this longitudinal study is to examine how children use hand-drawn sketching to expand and facilitate their design thinking for STEM-based activities. Typically associated with artistic expression, sketching can be used to quickly share ideas and communicate mental representations. The ways that children use sketching methods to communicate during a variety of activities in the Purdue sponsored GERI *Toy Design Lab in Mechanical Engineering*, and if there are any conclusions that can be drawn, were analyzed. Additionally, the ways in which color was used during sketching to communicate ideas was examined.

CHAPTER 8. GERI - TOY DESIGN LAB IN MECHANICAL ENGINEERING

The Gifted Education Resource Institute (GERI) was founded at Purdue University in 1974 by John Feldhusen to deliver an "innovative center dedicated to the discovery, study, and development of human potential" (Purdue University, 2016). Within GERI, there is a summer camp scheduled containing enrichment programs for gifted, creative, and talented students that have just completed grades 5-12. The different learning modules offered are classified according to age range; Comet is for grades 5 or 6, Star for grades 7 or 8, and Pulsar for grades 9-12. Designed for Star students (grades 7 or 8), the *Toy Design Lab in Mechanical Engineering* is a haven for designers and tinkerers.

8.1 Introduction

The *Toy Design Lab in Mechanical Engineering* is a two week workshop offered in two separate installments during the month of July 2016 at Purdue University. Presented here are the sketching-related observations made during the first session of the workshop and its 17 participants ranging in ages from 12-14. The 2016 installment is similar to the inaugural 2015 session (represented in Figure 19) in that there are a series of creative and engaging activities designed to send children into the throws of prototyping through ideation sketching, computer aided design, laser cutting, and 3D printing.

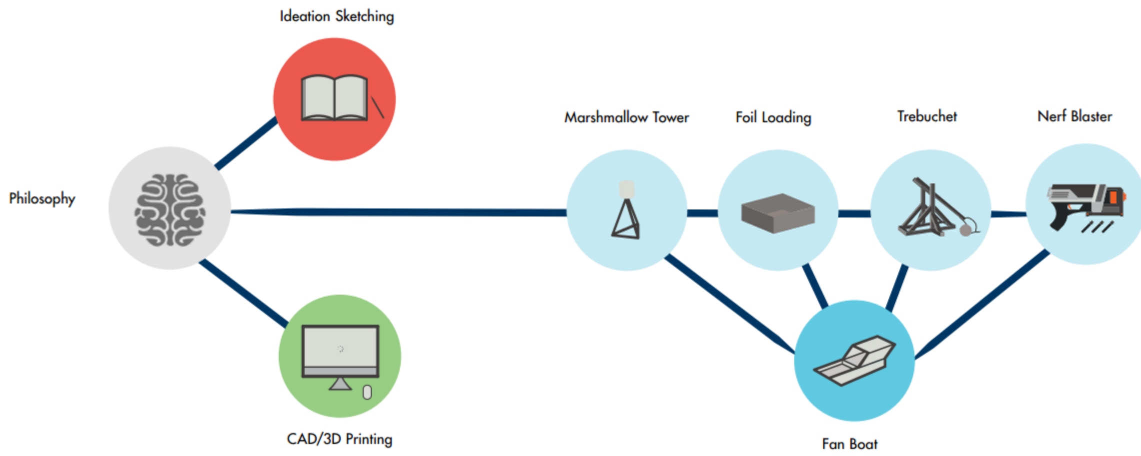

Figure 19. Inaugural 2015 GERI *Toy Design Lab in Mechanical Engineering* activities.

It is during these activities that the participants are fully immersed in the Maker Movement around which the workshop was designed.

8.2 Maker Motivation

At the heart of the Maker Movement is the idea that learning happens through design and making. Honey and Kanter state that "design-based learning engages students as critical thinkers and problem-solvers and presents science and technology as powerful tools to use in solving some of the world's more pressing challenges;" however, this concept is in contradiction to current educational practices which align success with "abstract thinking and high-stakes testing" (Honey and Kanter, 2013). With these stringent guidelines, there is no room for learning through play. The Maker Movement seeks to remedy this trend and give children an outlet where creativity is limitless, mistakes are encouraged, and curiosity is rewarded.

Honey and Kanter postulate that "design-make-play learning methodologies" have the "potential to foster young people's minds" (Honey and Kanter, 2013). Rooted in these methodologies is the idea that tinkering is essential for learning. Guest authors Resnick & Rosenbaum note that tinkering is a natural form of experimental play during which " makers are continually reassessing their goals, exploring new paths, and imagining new possibilities" (Honey and Kanter, 2013), as seen in Figure 20.

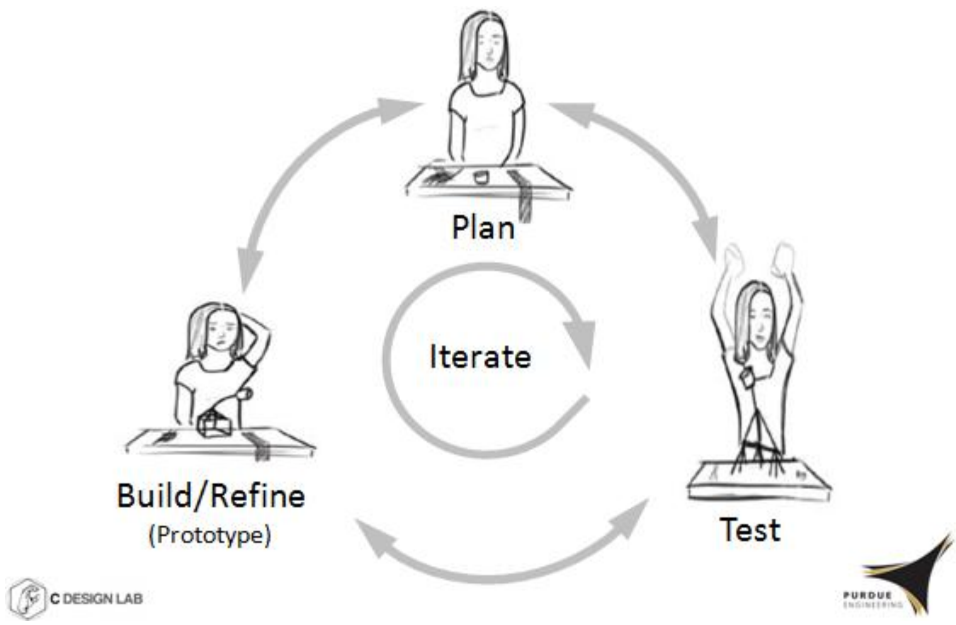

Figure 20. Iterating in GERI for design.

8.3 Activities

All activities are hands-on and encourage tangible design learning through iterative prototyping methods, such as: hand sketching, computer aided design, laser cutting, cardboard construction, and programming. Common to all activities are three questions that should be addressed:

- "What if we build it like this"?
- "Does it work?"
- "What can be improved?"

In the process of answering these questions, participants work the steps of the i8^{TM}framework (Figure 21) for innovative toy design that was developed in conjuncture with Purdue University's Computer Aided Design and Rapid Prototyping (ME444) course.

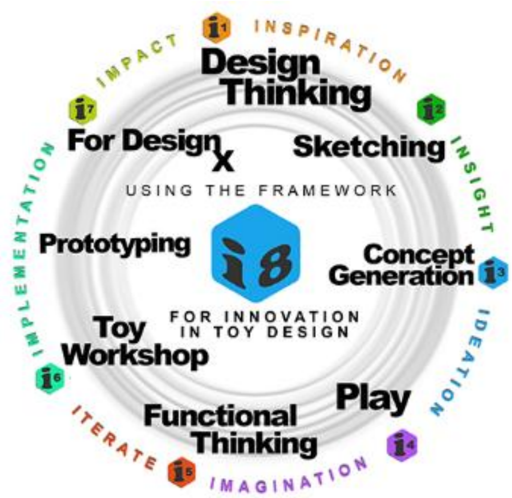

Figure 21. i8^{TM} framework (Purdue University, 2016) for toy design.

The activities for the workshop were designed and distributed in such a way that the skills and knowledge learned compound with each activity. Simple engineering concepts are learned early on in the workshop while design toolkits expanded as the days progressed. All of the skills learned in prior activities will come to fruition in the final challenge; *engi-crafting* a robot skit with characters and storylines that the children design, build, and program themselves.

8.3.1 Marshmallow Tower

For this challenge, the design goal is to concept and construct a tower as tall as possible out of spaghetti sticks that can support a marshmallow without toppling over. During this activity, designers start building a foundation of basic engineering principles, including strength of materials and statics.

8.3.2 Sketching Workshop

The primary objective of the sketching workshop was to learn how to rapidly visualize and communicate ideas. Using pencils, markers, and paper children are able to utilize sketching as a form of thinking.

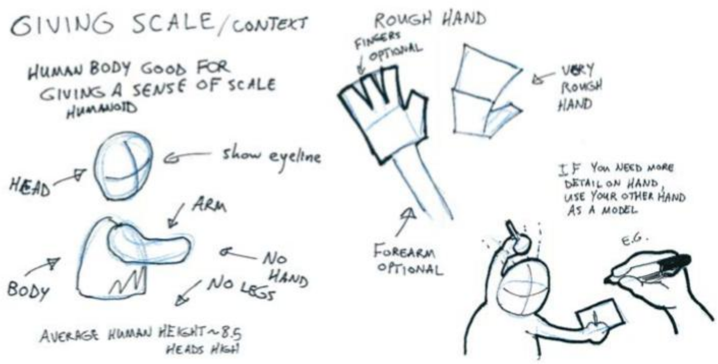

Figure 22. Example sketching instructions similar to what is shown during workshop.

8.3.3 NERF Blaster Challenge

For this challenge, participants were tasked with dissecting a NERF Blaster toy, learning about the parts, and reassembling it in the proper sequence. The ultimate goal of this exercise was to get a sense of how things function on both a component and system level.

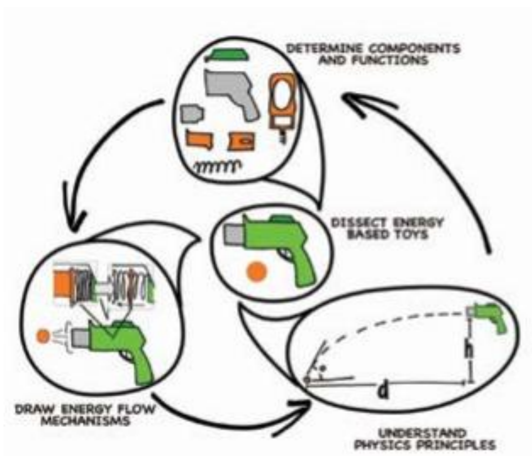

Figure 23. NERF Blaster individual part and assembly familiarity.

8.3.4 CAD and Cardboardizer

During this session, students became familiar with computer aided design tools and concepts used for rapid prototyping.

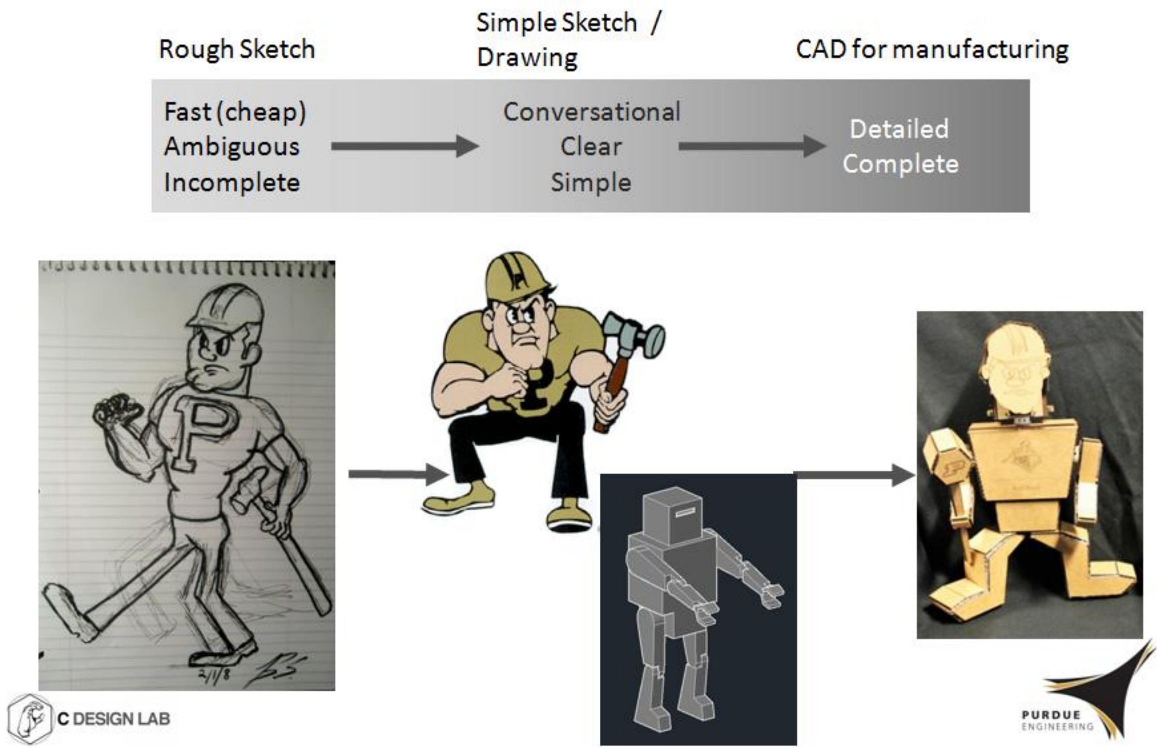

Figure 24. Design of a robot character taken from initial sketch to Cardboardizer.

8.3.5 Automata and Mechanisms

The primary goal of this activity was to understand how complicated machines use combinations of simple mechanisms to provide desired outputs.

8.3.6 Task-Oriented Zirobots

This challenge allowed the children a chance to construct a Zirobot and program it to perform certain tasks which acted as a precursor to the overall Ziro Skit that closes the two week workshop.

Figure 25. Example of a task-oriented Zirobot.

8.3.7 Ziro Skit

Using all of the knowledge and skills acquired during the lab, the children were tasked with designing and constructing a robot skit. All theatrical elements, from script to set, were designed by them. They designed functioning cardboard characters that came to life through the integration of Ziro modules. As an added challenge, the characters had to perform certain movements that were designated by the instructors.

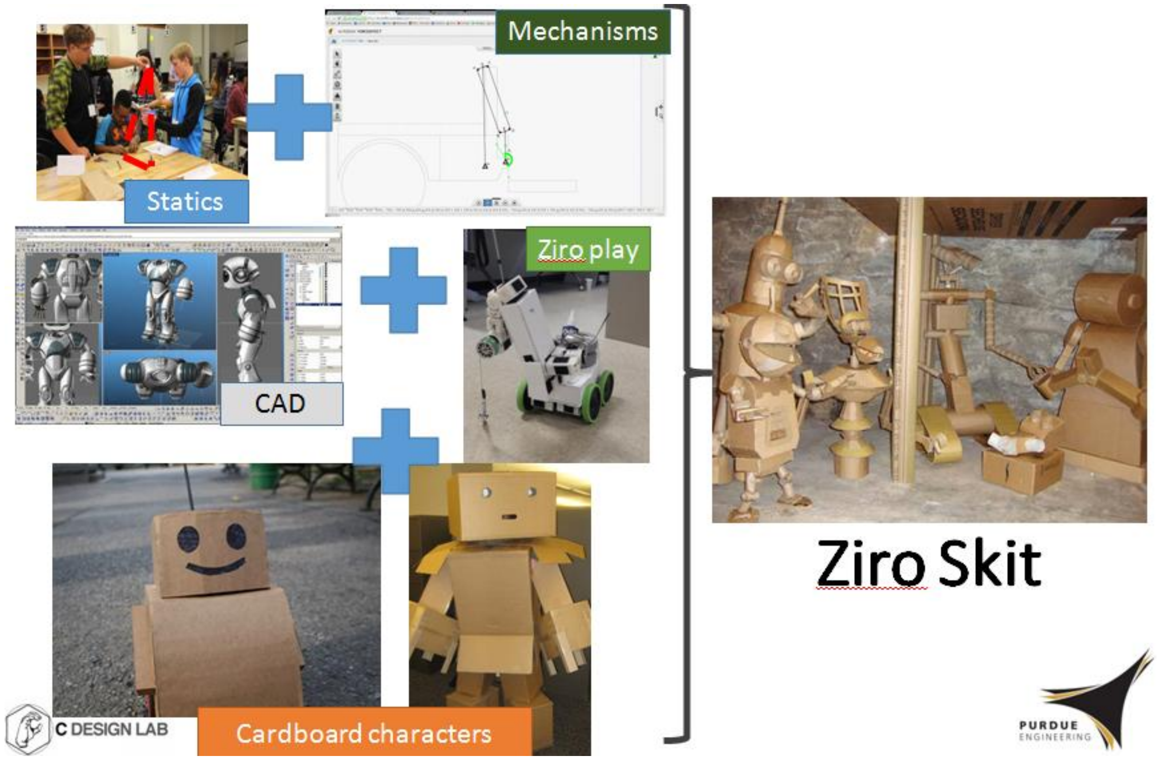

Figure 26. Putting together all of the components from the Lab to form the Ziro Skit.

The activities that this observational research focuses on are those that purposefully implemented hand sketching; Marshmallow Tower, Sketching Workshop, and the NERF Blaster challenge.

CHAPTER 9. MARSHMALLOW TOWER

9.1 Activity Motivation and Agenda

9.1.1 Motivation Behind Marshmallow Tower

In the Marshmallow Tower activity, students were tasked with designing and building the highest freestanding tower possible in 18 minutes. Complexity was added to this challenge in that the tower must be constructed of uncooked spaghetti noodles while supporting the weight of a single marshmallow. In its essence, the purpose of the challenge was to help students identify basic engineering design principles through iterative rapid prototyping.

With a clearly defined design objective and no obvious path to resolution, the Marshmallow Tower challenge is a great example of real-world engineering solution generation. With the open-ended paths available to the designers, there is ripe opportunity for experiencing operational learning, such as brainstorming, time management, and team work, as well as engineering design-based learning, such as strength of materials and safety.

One of the primary concepts reinforced during the challenge was the strength of shapes, with particular emphasis on triangles. Triangles are often used in construction for stability in many designs, such as the bridge in Figure 27.

Figure 27. Strength of shapes in real-world engineering design.

Triangles are a preferred shape for stability because their angles are fixed based on the opposite side length, which prevent the shape from collapsing. Other shapes, such as the square in Figure 28, collapse when the angles between the structural members change.

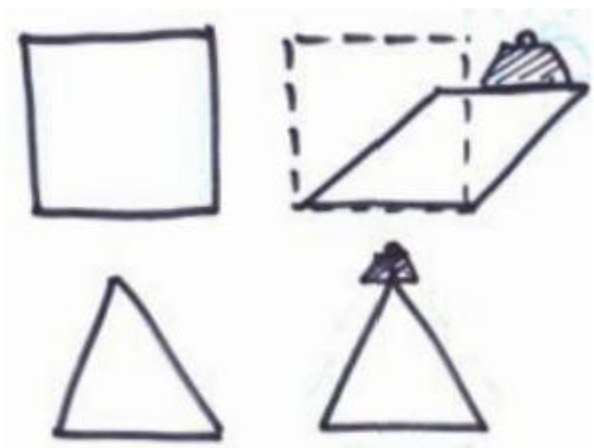

Figure 28. Deformation of shapes.

In addition to the strength of shapes knowledge, participants received first-hand experience with the properties of bending, tension, and compression, as well as a better understanding of force distribution. Through various design iterations, the participants got a sense of what worked by visually identifying the characteristics displayed in Figure 29, whether or not they are familiar with the mechanics of the concepts.

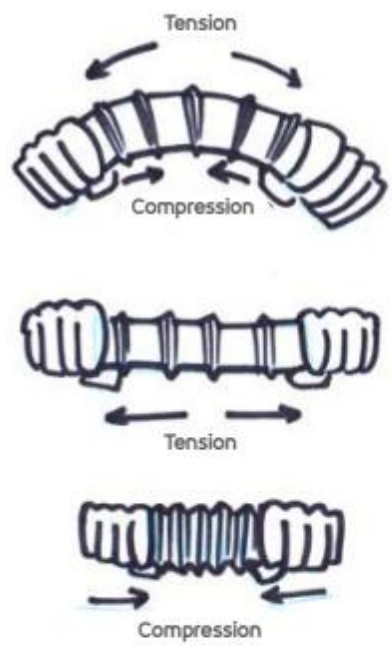

Figure 29. Visual representation of bending, tension, and compression.

9.1.2 Agenda to Setting Up Sketching Portion

After a brief introduction to the proposed challenge, the materials for construction, seen in Figure 30, are distributed to each student team.

Figure 30. Marshmallow Tower Challenge materials.

Each student was then given a pre-survey containing questions that related to sketching, the details of which are discussed in Chapter 12: Methodology and Results. Immediately upon completion of the pre-survey, the challenge of designing and prototyping the tower began. In this design space, there were expected to be multiple iterations of towers ideated by the student teams. One of the primary tools available as an outlet to these ideations was sketching.

9.2 Ideation Sketching

Built into the challenge, it was intended that students sketch out their proposed designs in conjuncture with prototyping. With each iteration, the sketches should ideally progress to show the changes in design thinking. Such differences in design can be seen in the example conceptual drawings in Figure 31.

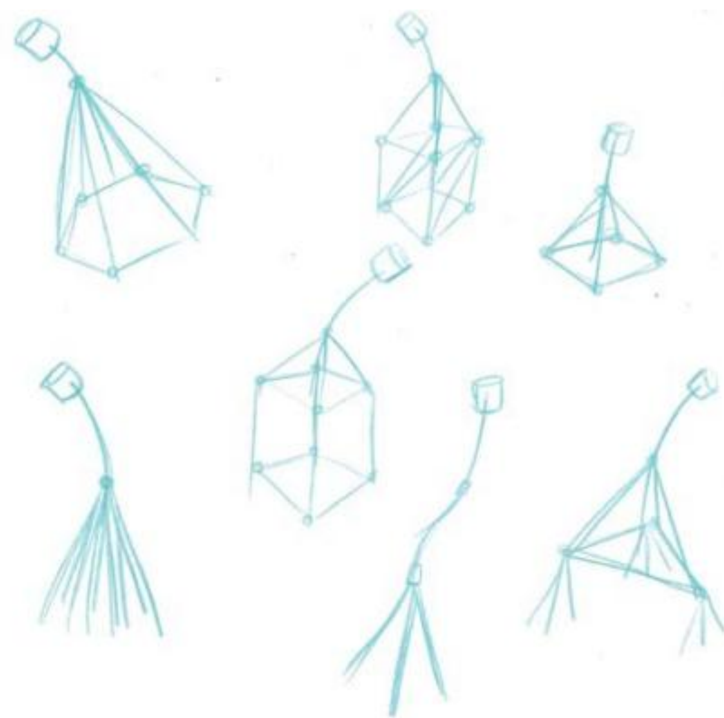

Figure 31. Examples of ideation sketching during the Marshmallow Tower Challenge.

During the challenge, workshop facilitators took pictures of the towers that the students built.

9.2.1 Tools for Sketching

As this is one of the first activities of the overall workshop, the tools used for sketching were introductory. Simply, there was a large central pad of paper for group sketch, pens, pencils, and markers. In the later sketching workshop, the children used the same tools, but advanced their methodologies with which to use them.

9.2.2 Teamwork and Collaboration Schemes

For the Marshmallow Challenge, student teams were instructed to ideate as a group on a single pad of paper. While there can be individual contributions to the design, the final product, as well as the journey there, were collaborative efforts.

CHAPTER 10. SKETCHING WORKSHOP

10.1 Activity Motivation and Agenda

10.1.1 Motivation Behind Sketching Workshop

The purpose of this activity was to develop the skills used for design sketching, a great tool for brainstorming ideas. While practicing these skills and employing the tips offered by the instructors, the children gained an introduction to the nature of sketching, as well as the importance of annotations and good posture while doing so. By the end of the activity, the participants were intended to be able to communicate their ideations through sketching practices without inhibitions.

10.1.2 Agenda

After a brief lecture of the benefits and uses of sketching, the children were given a pre-survey meant for future analysis by the workshop's facilitators. The details of this survey can be found in Chapter 12: Methodology and Results.

The initial activities of the workshop were intended to get the children familiar with the concepts of sketching and instill confidence in its purpose and qualities. The instructors gave an introduction to sketching that included an explanation of the difference between sketching and drawing. After the introductions, the participants transitioned into sketching exercises including drawing straight lines and circles. Once the framework was initiated, a brief overview of good posture coupled with additional activities to remove inhibition were carried out. Examples of these activities included showing a person's size in context by adding a building to the sketch. To expand on the current sketching toolkit, concepts to increase detailing for communication were presented. These included shading, line weights, annotations, and showing motion with things such as arrows and symbols.

10.2 Tools for Sketching

The set of tools that each participant used for this exercise are common artistic utensils commonly utilized by children; paper, markers, and pencils. These tools were chosen because they are familiar to children and are available in abundance. The pencils offer the opportunity for gentle shading and initial construction. With less pigmentation than makers or pens, mistakes can be made using pencils with little degradation to the design. Markers were also available in the event that they were the preferred tool of choice, and to add any outlining or detailing that the children thought were important.

CHAPTER 11. NERF BLASTER

11.1 Activity Motivation and Agenda

11.1.1 Motivation Behind NERF Blaster Challenge

For the NERF Blaster Challenge, participants were tasked with disassembling and studying the mechanisms used in the toy. During this activity, it was intended that the children learn how dissection can inspire design conceptualization.

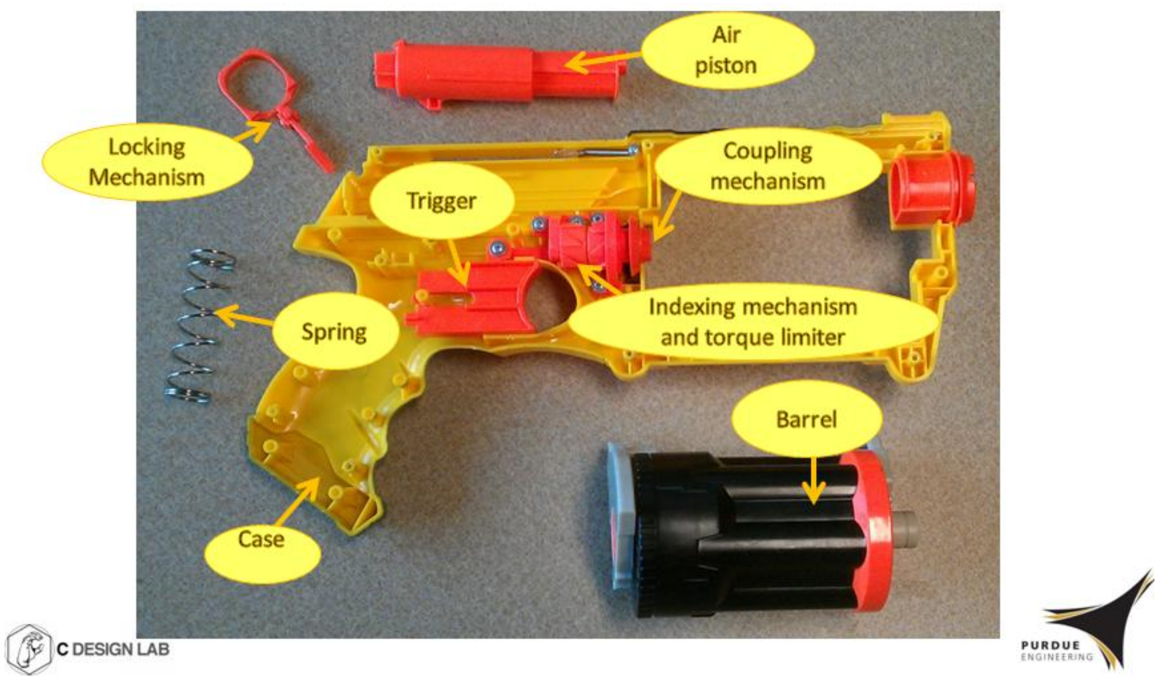

Figure 32. Example NERF Blaster assembly dissection with individual components labeled.

11.1.2 Agenda to Setting Up Sketching Portion

After a brief introduction to the activity, each student was again given a pre-activity survey, details of which can be found in Chapter 12: Methodology and Results. Once the survey was completed, the children were instructed to disassemble their NERF Blasters and then sketch each of the components.

11.1.3 Use of Color

This activity introduced the use of color as a possible enhancer to design ideation, which currently is a relatively unexplored thought process. For the experiment, numerous colors of drawing utensils (whether pens, pencils, or markers) were available to the participants for the purpose of generating their NERF Blaster sketches. Limited instruction was given for how to use the extra colors, such as differentiating close-proximity components. It was predicted that color could be used to:

- Convey motion of components, as seen in Figure 33

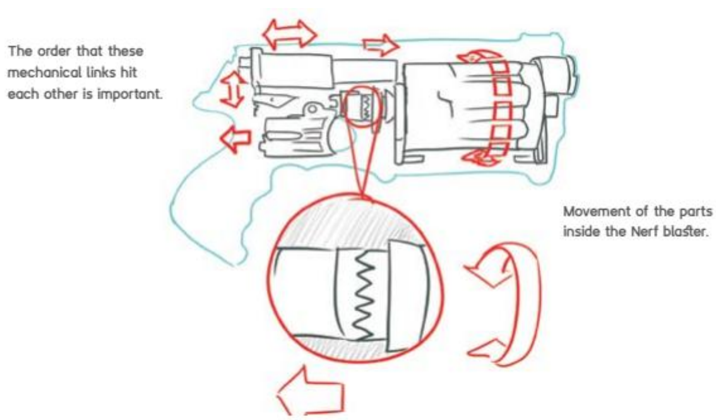

Figure 33. Using color to highlight motion in a sketch.

- Add aesthetic appeal
- Highlight certain features of the sketch
- Differentiate design iterations, such as using a different color for each step in design thinking
- Differentiate close-proximity or overlapping components, as seen in Figure 34

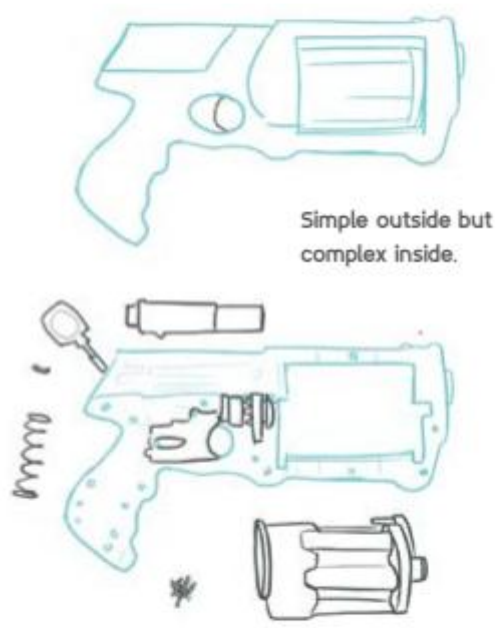

Figure 34. Using color to differentiate components and features.

11.2 Tools for Sketching

Similar to the previous activities, the students were provided with a sketching surface along with pens and pencils; however, all were slightly iterated from the previous activities. For this particular activity, tracing pads with semi-translucent paper were used for sketching. The purpose of using this paper was to see how they used the paper to overlay sketches to see differentiations in their designs. It was possible that they would find different ways to use the paper as well, such as using the multiple layers of semi-see-through paper to sketch each component individually and then overlay to form the completed gun. Similar to the previous activities, additional colors for the sketch pens and pencils were made available. One of the primary focuses of the sketching analysis for this activity was to observe how the students used additional colors to facilitate their design ideations.

11.2.1 Teamwork and Collaboration Schemes

For the NERF Blaster Challenge, participants received an individual set of tracing paper with which to map out their designs. From these individual sets of paper, they were able to complete the design sketching either as a team or individually.

CHAPTER 12. METHODOLOGY AND RESULTS

12.1 Data Collection

The data collection method was similar for the three GERI activities; Marshmallow Tower Challenge, the Sketching Workshop, and the NERF Blaster Challenge. All data gathering methods were designed to provide little to no interference to the children during their activities. The primary methods of data collection for this particular study were reviewing participant written responses in pre-activity and post-activity surveys as well as real-time observations made by the 2016 GERI *Toy Design Lab in Mechanical Engineering* facilitators. With only 17 participants, there are not enough data points to be able to offer any type of meaningful statistical significance. Therefore, this work acts to establish a foundation built upon initial observation on which future in-depth sketching analyses can be facilitated.

Additionally, GoPro cameras stationed above each table workstation were used to capture both audio and visual recordings of design ideation progression in real-time. However, these recordings were not considered due to time constraints. They will be reviewed and analyzed after the conclusion of the month-long workshop by the author and other facilitator for future publications (as noted in Future Work).

12.2 Marshmallow Tower

12.2.1 Analysis Framework

The primary methods of analysis for this activity were reviewing the results of the pre- and post-surveys as well considering any real-time observations that were made while the activity was taking place. Pre-activity surveys were distributed containing the following sketching questions:

- Sketch the idea for your tower.
- Why is sketching important for design?

After the pre-activity survey was completed and the activity initiated, real-time observation took place. Key items that were paid particular attention to during observation included:

- excitement level of the participants
- interest level of the participants
- frequency of sketching for design iterations

After the challenge was completed, all participants filled out a post-survey containing the following sketching-related questions:

- Sketch the model of the tower that your team created. If you created multiple designs, sketch the one that worked best.
- Did sketching help you with designing your tower? Please explain.

- Please circle all of the words that describe the sketching portion of the challenge:

Boring	Fun	Working together
Easy	Challenging	Hard
Creative	Interesting	Finding solutions
Working by myself	Worthwhile	Pointless
Exciting	Messy	New ideas

Comparison of the pre- and post-survey questions allowed the students and facilitators to see how design thinking changed through the challenge.

12.2.2 Results

In addition to being asked to sketch their initial idea for what the tower should look like, they were asked why sketching is important for design. All answers were positive towards sketching. The most common answers were that sketching helps the designers have a plan, find or create ideas, visualize, and generate ideas.

One of the primary findings made while observing the children constructing their towers and iterating their designs was that none of them sketched while iterating even though all of them implied in the pre-activity survey that sketching was important for design. It appeared to the observer that the children were practicing a form of mental sketching and creating physical sketches by iterating the physical design continuously and using gestural communications, such as in Figure 35. The only sketching that the students performed was in the pre- and post-activity surveys.

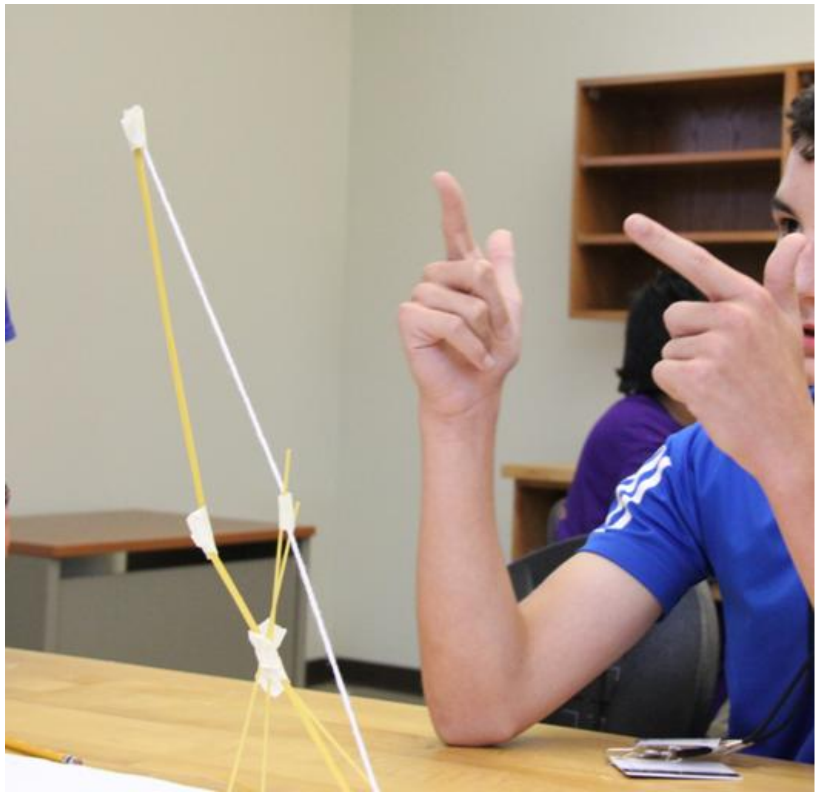

Figure 35. Using gestures to communicate design ideas.

Comparing the sketches in the pre- and post-activity surveys showed freeform design thinking transform to structured designs in the end. In many of the pre-activity surveys, there were smudges and messy lines that suggested the students kept changing their designs when trying to suggest an initial tower, (see Figure 36, item 1). Many of the post-activity surveys contained sketches that contained minimal rework and a sense of finality, most likely because they were sketching the final design and no iterating was necessary, (see Figure 36, item 2).

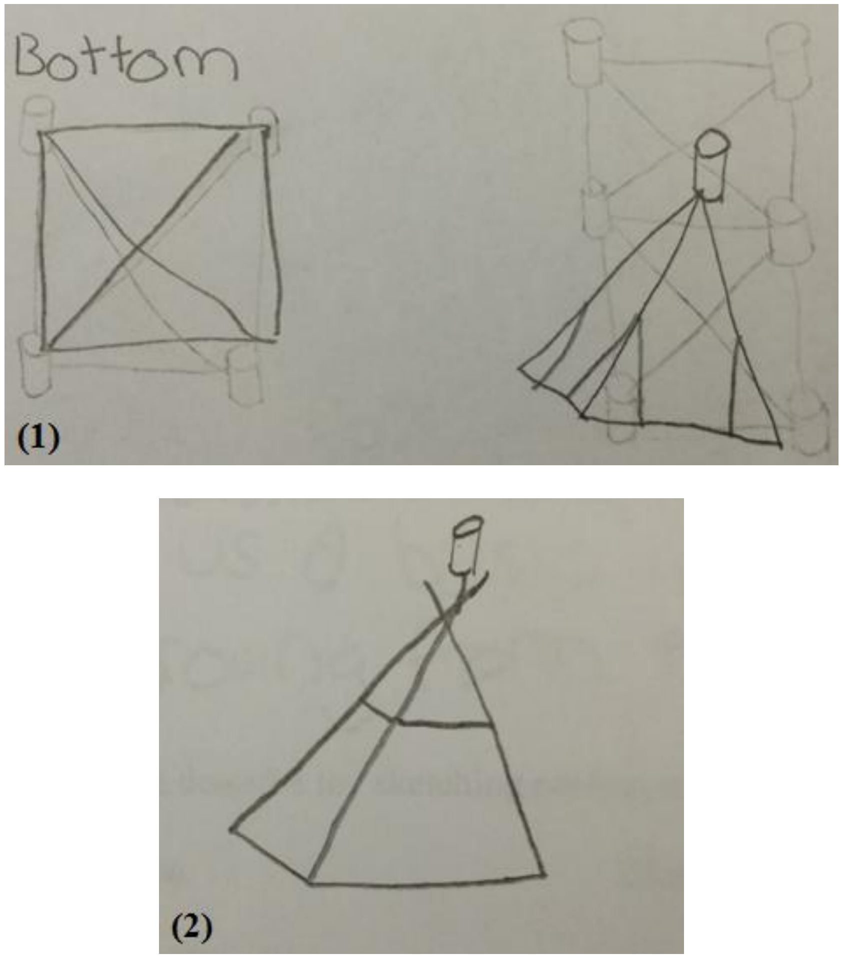

Figure 36. Pre- and post-activity drawings of marshmallow tower - item (1) is the pre-activity survey sketch, item (2) is the post-activity survey sketch.

To gain an overall sense of how the children felt while sketching, the post-activity survey included a reflective question asking how they would describe sketching with the ability to be able to select as many options as they wished. The results of this question are Pareto-distributed in Figure 37.

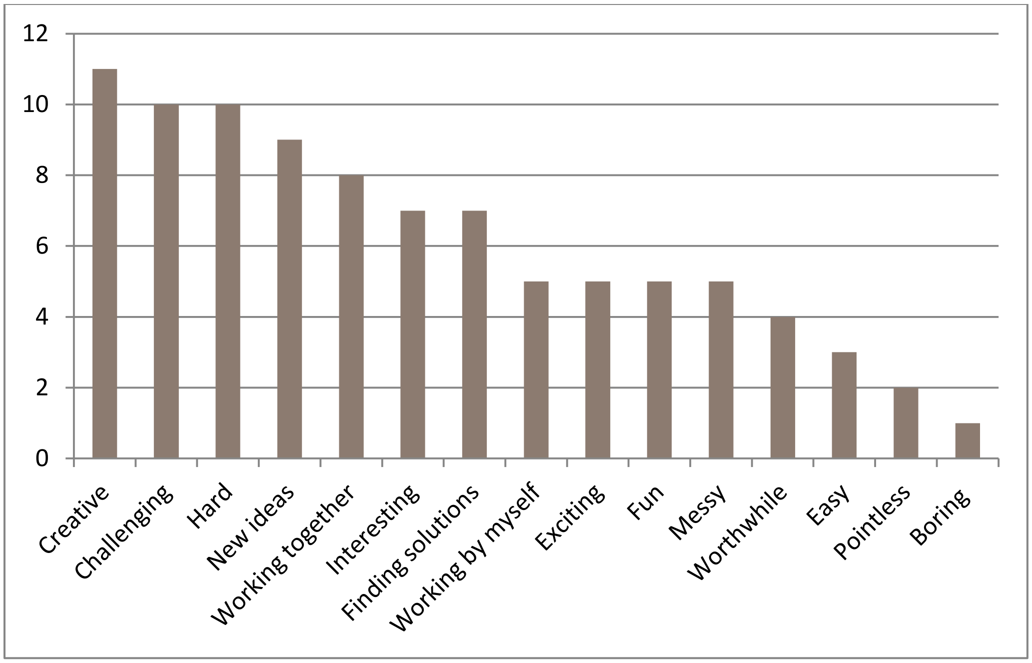

Figure 37. Participants' chosen descriptive words for sketching in the challenge.

The most common response was that sketching was creative; however, the second most common answer was that it was challenging. Analyzing the responses shows that there is a mix in feelings towards sketching, both positive and negative. More data points through future studies may be able to offer a more conclusive analysis.

When asked if sketching helped them with designing the tower, 9 students said yes and 7 said no. Along with being asked to elaborate, several of the students that answered yes said that sketching helped with designing their tower because it allowed them to plan, think of ideas, helped with coming up with initial design, and think through the design process. Some of the students that answered no said that sketching didn't help because they liked to design by just doing it, they didn't follow the designs that they came up with, they prefer to think through it and design in their head, and because others had ideas.

12.3 Sketching Workshop

12.3.1 Analysis Framework

Similar to the Marshmallow Tower Challenge, the primary methods of analysis were review of the participant surveys and real-time observations. The pre-activity survey was given to the children after an initial introduction to the benefits and uses of sketching for design. The following questions were included:

- Do you tend to think in words or pictures?
- Effectively communicate how a Jack-in-the-Box works
- When explaining your ideas to others do you prefer sketching or verbal communication? If someone was explaining their idea to you, which would you prefer? Why?
- What is the difference between a drawing and a sketch?
- Do you think a sketch can effectively communicate a design on its own without any extra explanation? Why or why not?
- Which color do you prefer in sketching? Why?

At the end of the sketching workshop, the students were given a post-survey that included the following questions:

- Which part of sketching do you think is the easiest? Please circle only one.

Shading	Giving scale	Drawing initial shapes
Thinking of what to draw	Thinking of how to draw it	Connecting the shapes
Adding features, details	Outlining	Showing motion

- Which part of sketching do you think is the hardest? Please circle only one.

Shading	Giving scale	Drawing initial shapes
Thinking of what to draw	Thinking of how to draw it	Connecting the shapes
Adding features, details	Outlining	Showing motion

The primary goals of the surveys was to gain an understanding for how children use sketching for design and if their conceptions of it changed during the workshop.

12.3.2 Results

Since the entire activity was based around sketching, the corresponding surveys produced a lot of insight into the group's perspectives on sketching. When asked if they tended to think in words or pictures, the results showed that the majority of those that answered the questions thought in pictures. 8 participants indicated that they think in pictures, 4 in words, and 3 participants suggested that they think in both pictures and words. When asked to communicate how a Jack-in-the-box works, 8 children used words to describe the process and 9 used sketching. This correlates with the responses in the previous question.

With regards to preference of sketching or verbal communication when receiving or explaining ideas to others, the responses were mixed. Many of the answers were general and difficult to understand, most likely because there were too many questions to be answered. For explaining ideas to others, there was a mix of words and sketching. Some of the most interesting responses were:

- "I do words because everyone else understands words"
- "I use verbal communication, but depending on the project sketching works better because it allows you to visualize the idea"
- "Sketching because it can show things that don't have a word for it"

Interestingly, most of the responses directly answering the question indicated that they preferred sketching when someone else was explaining an idea to them.

- "Sketching because I'd probably forget what the person was talking about"
- "Sketching helps me see things better"
- "I like others telling me because I can put a picture of it in my mind"
- "Sketching - I learn things easier with non-verbal methods"

Interestingly, when asked if they thought that a sketch could effectively communicate a design on its own without any additional explanation, the responses shown in Figure 38 conflicted with the previous responses.

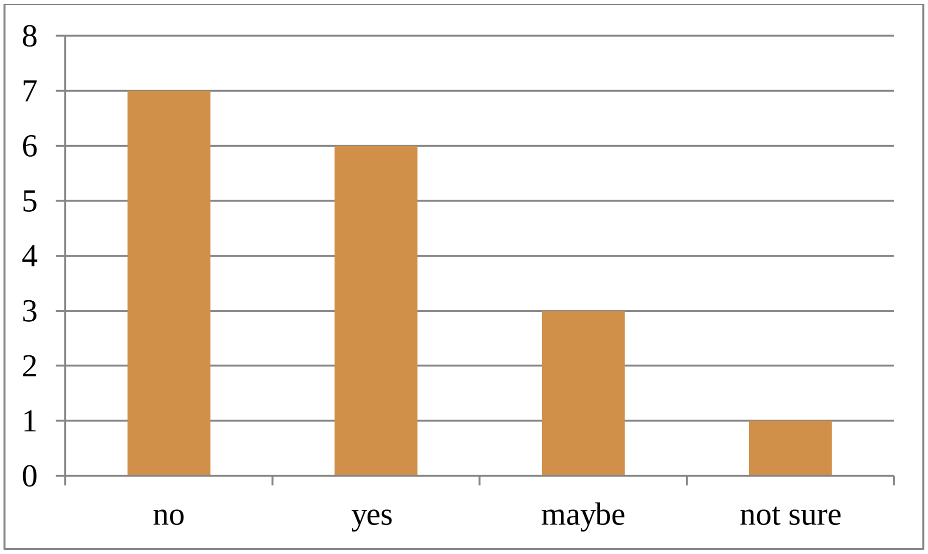

Figure 38. Sketching communication - can a sketch effectively communicate a design on its own without any additional explanation?

When asked if they could describe the difference between a drawing and a sketch, the responses were all similar. Similar themes emerged when describing drawings; detailed, requires time and patience, and refined. Sketches were summarized as simple, quick, messy, practice, and a rough drawing. One of the students illustrated their response by drawing a simple stick figure and sun for the sketch, and then drew a more detailed person with clothing, accessories, and a more detailed landscape for the drawing.

Finally, for the pre-activity, the students were asked their preferred color for sketching. Some answered with multiple colors; all answers were considered since it would have been hard to differentiate the primary choice for those that answered with multiple colors.

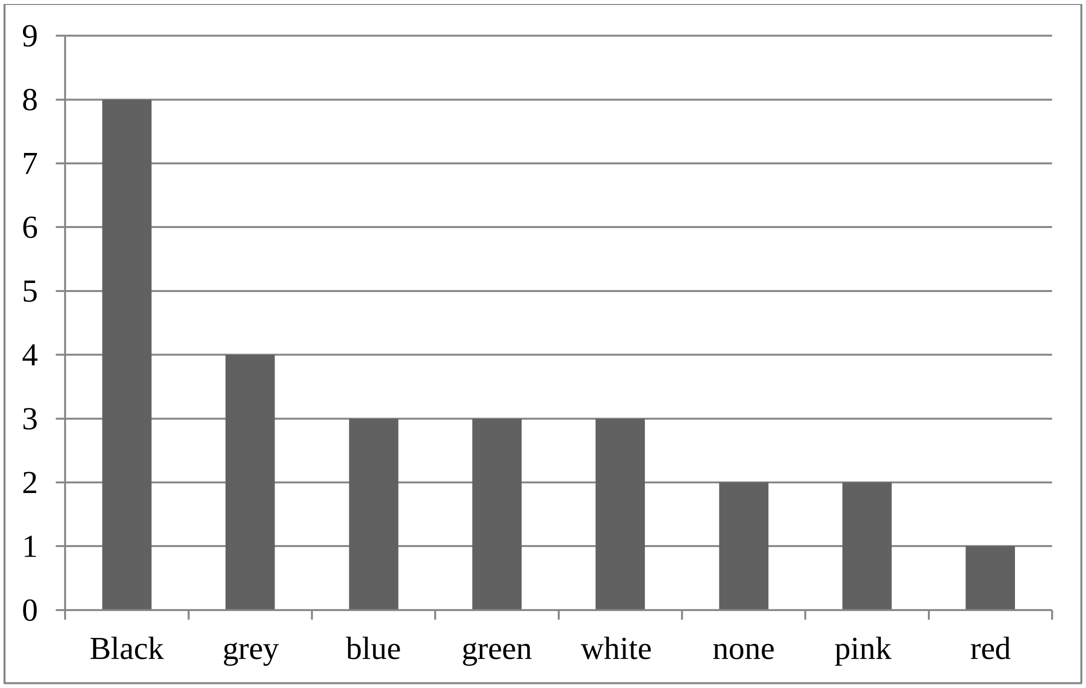

Figure 39. Participants' preferred colors for sketching.

The results in Figure 39 show that the most popular color choices were black and grey. Discounting white and (none), there were 9 colorful responses. This indicates that the majority preferred non-colorful sketching.

While observing the workshop, it seemed as though engagement was minimal. It was difficult to surmise if the kids were bored or just thinking. There was not much discussion during the interactive instruction part of the workshop. Enthusiasm seemed to be minimal when being instructed to go through the various concepts of line weights, circles, and context. A lot of children had a hard time understanding the concept of context of size. It is believed that additional visual aids would have assisted in their understanding of this.

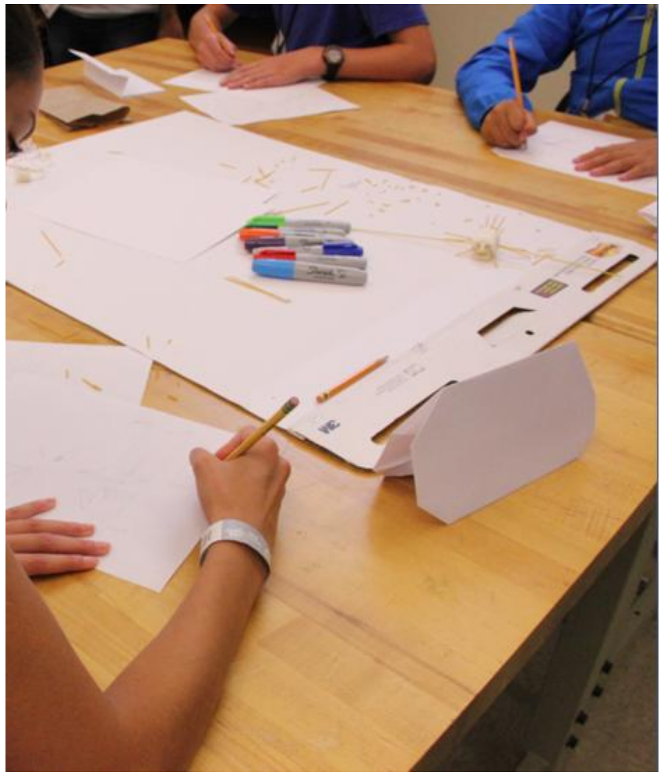

Figure 40. Students practicing sketching concepts.

The post-activity survey contained only two prompts; identify the easiest (Figure 41) and hardest (Figure 42) parts of sketching. The students were asked to only circle one answer; however, some students selected more than one. Not wanting to discount any responses, all perspectives were considered; however they are noted in the results as being answered incorrectly. Those that selected only one choice correspond to the correctly answered results.

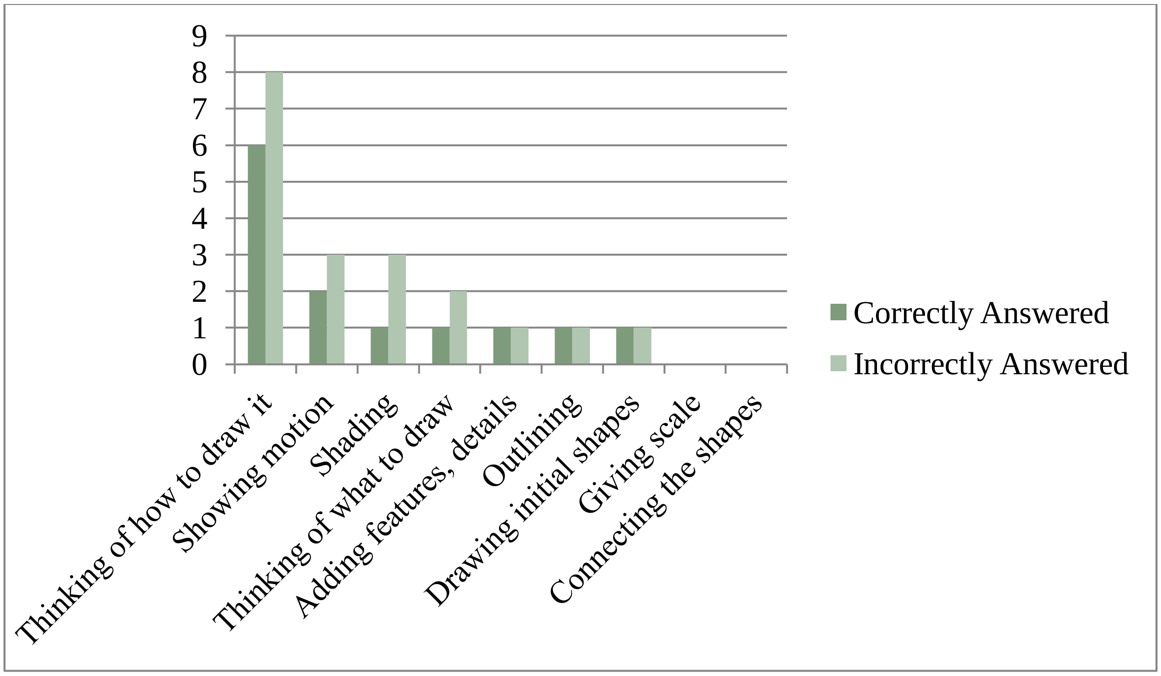

Figure 41. What was the easiest part of sketching?

Overwhelmingly, the most common response was that thinking of how to draw something was the easiest part of sketching. Interestingly, the most popular response for the hardest part of sketching was thinking of what to draw. These findings suggest that the majority of students have difficulty determining what design they want to draw, but have relative ease in planning how to draw it once their design is selected.

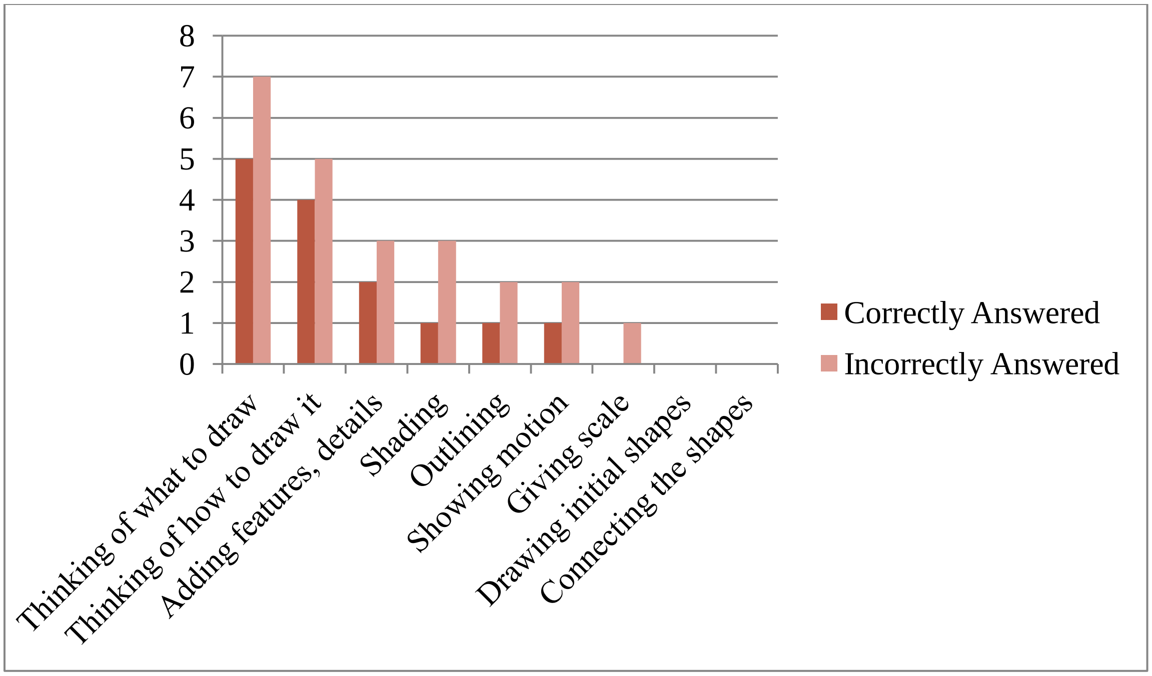

Figure 42. What was the hardest part of sketching?

Before the next day's challenge (NERF Blaster) started, the children were verbally asked for some sketching feedback based on the lessons learning during the previous day. Primarily, they were asked if they thought they could have used sketching to better design their Marshmallow Tower after going through the Sketching Workshop. One kid answered and said it would have been useful because it could have provided a blueprint that they could build from and then change their design from. What was most interesting about this response is that the same individual said in their Marshmallow Tower Challenge surveys that they didn't think sketching was useful at all and they like to do all design thinking in their head. This suggests that going through the Sketching Workshop and learning the benefits of using sketching for STEM design changed the perspective on this methodology for at least one of the participants.

12.4 NERF Blaster

12.4.1 Analysis Framework

After a brief introduction to the NERF Blaster Challenge, the children were given a pre-activity survey that contained the following sketching-based questions:

- What do you think throws the Dart forward? Explain with sketch.
- Do you think it would be difficult to sketch each of the components?
- Do you think you will use any other colors to sketch the NERF Blaster? If so, why?
- If you were going to use a color to sketch the "air" trailing behind a NERF foam arrow, what color would you use? Why?

After the activity had ended, students were given a post-survey that contained the following sketching questions:

- How many colors did you use to sketch the toy?
- Did color help you with the sketching exercise? If so, why/how?
- Please circle all of the words/phrases below that describe how you felt using different colors for design during the sketching portion of the activity:

Fun	Didn't help	Creative
Helped a lot	Easier to add detail	Helped a little
Didn't use color	Made design confusing	Hard to use
Want more colors	Exciting	Made design less confusing

In addition to survey review and real-time observation, each of the participant's sketching pads were reviewed. Key sketching items that were examined included:

- excitement level of the participants
- interest level of the participants
- Number of colors used overall
- Number of pages used in the sketchbook

The primary observation goal of this activity was to understand if color is a useful tool for children when sketching their ideas and designs.

12.4.2 Results

The primary sketching activity here was to sketch each of the components for the NERF Blaster. When asked if they thought it would be difficult to sketch each of the components, most of the participants indicated that they thought it would be difficult, (see Figure 43).

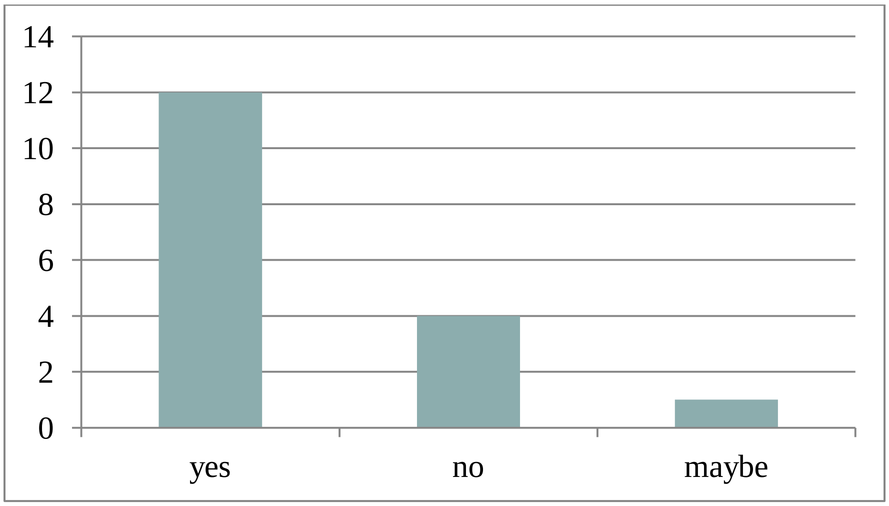

Figure 43. Will it be difficult to sketch each of the components?

Thinking about how the NERF Blaster works, the students were asked to explain with a sketch what they think throws the NERF dart forward. The most common response received was a combination of sketching and words, see Figure 44.

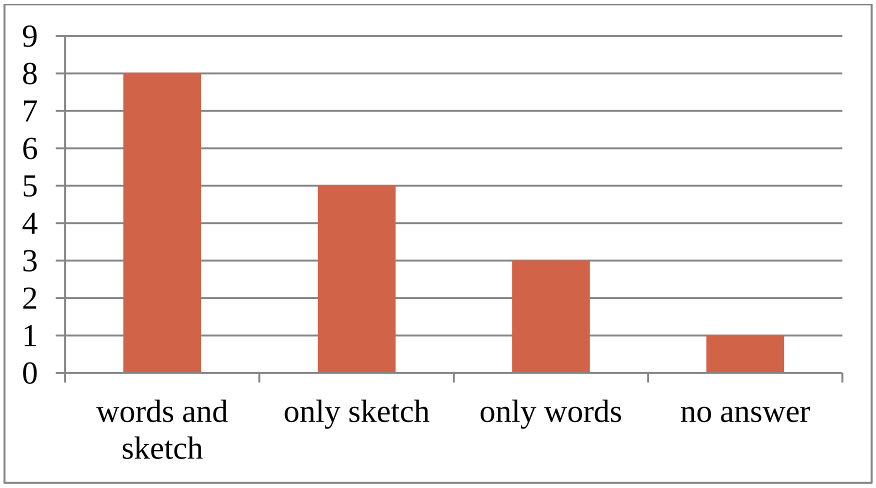

Figure 44. Method of explaining a blaster function.

Examples of these types of response are shown in Figure 45.

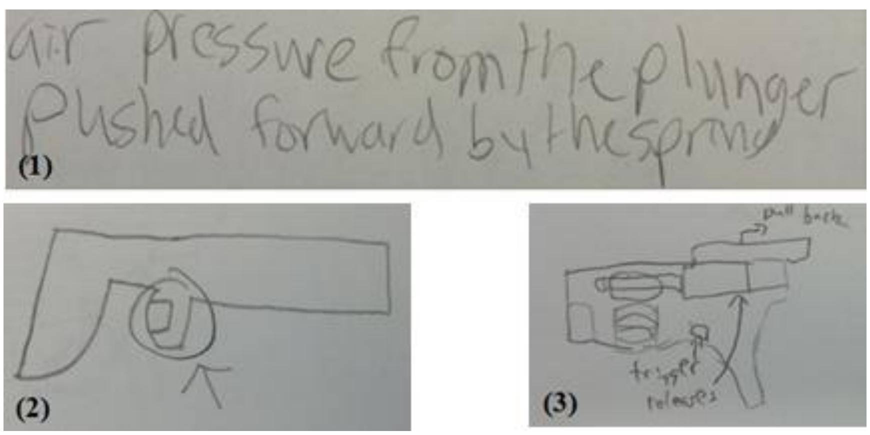

Figure 45. Pre-activity NERF sketching - (1) contains only words, (2) contains only sketching, and (3) is a combination of words and sketching.

Color usage was analyzed heavily here. Each of the students were asked in the pre-activity survey if they thought they would use additional colors to sketch the NERF Blaster. 9 indicated they planned to, 7 said they would not, and 1 was not sure. They were also asked to think creatively and indicate which color they would use to show the "air" trailing behind a NERF foam arrow in a sketch. 9 of the 16 participants that answered the question responded with a shade of blue with most defending their selection by associating blue with the color of the sky.

Before the children started the activity, the instructors gave them some ideas for what color could be used for to help with design thinking. These suggestions included showing motion and differentiating components. Additionally, the instructors gave the children some insight as to what the tracing paper could be used for, such as overlaying separate components to form the full assembly.

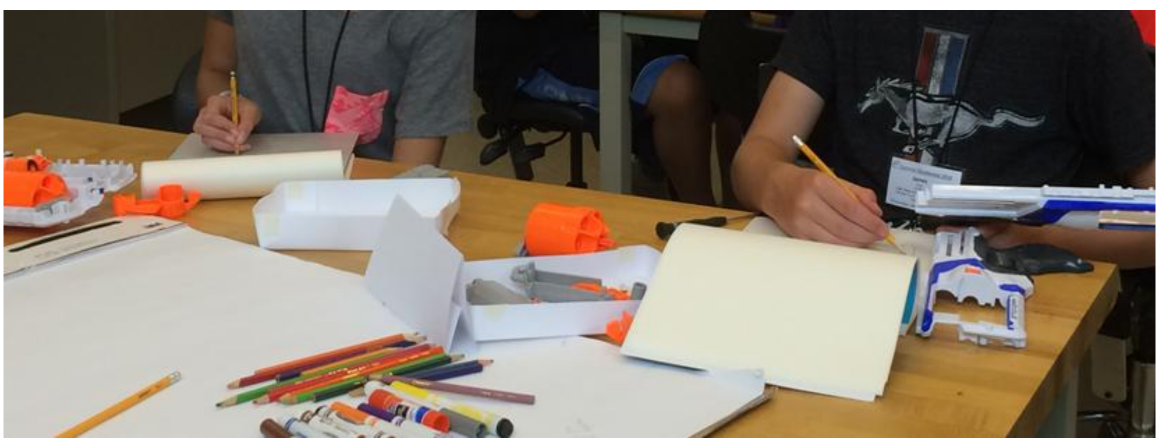

Figure 46. Sketching NERF Blaster components.

It was observed that a lot of the students started sketching towards the back of their pads and then moved towards the front of the pad with each new sketch. They said they did this so that they could layer the sketches. Figure 47 is a great example of one student's attempt to practice the layering technique.

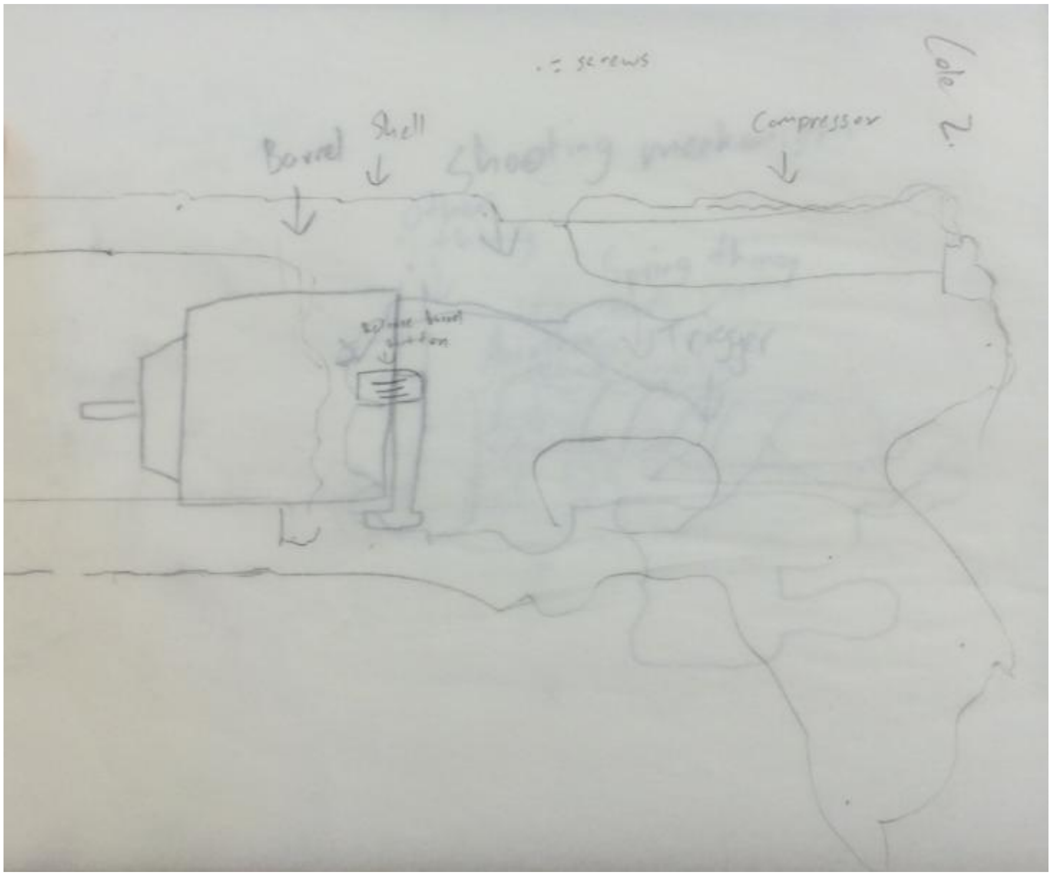

Figure 47. Multiple sketches overlaid to form a single assembly.

They drew a separate component on 10 different tracing sheets (Figure 48) and layered them to form an assembled blaster (Figure 47).

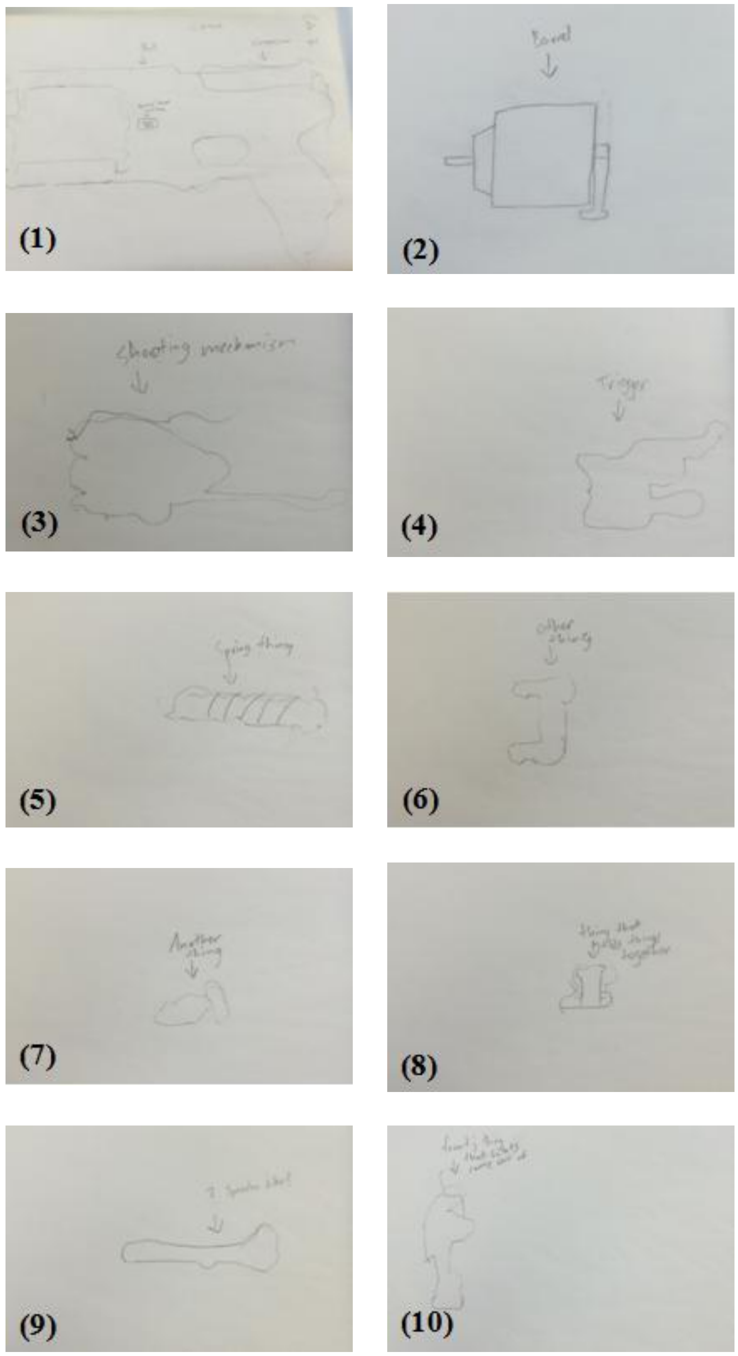

Figure 48. 10 individual sketches for within the NERF assembly.

Overall, the students appeared more engaged compared to the previous day's sketching activities. The instructors theorized this was most likely due to them having a tangible object to draw and not an arbitrary activity, such as sketching size context for abstract figures. It was also observed that all children were using ordinary lead pencils at first for sketching. Instructors continually reinforced that color could be used for design sketching; however, this had minimal impact on the students. There were a few students that utilized color, though. One used both color and layering to identify details and compartments of the blaster (Figure 49).

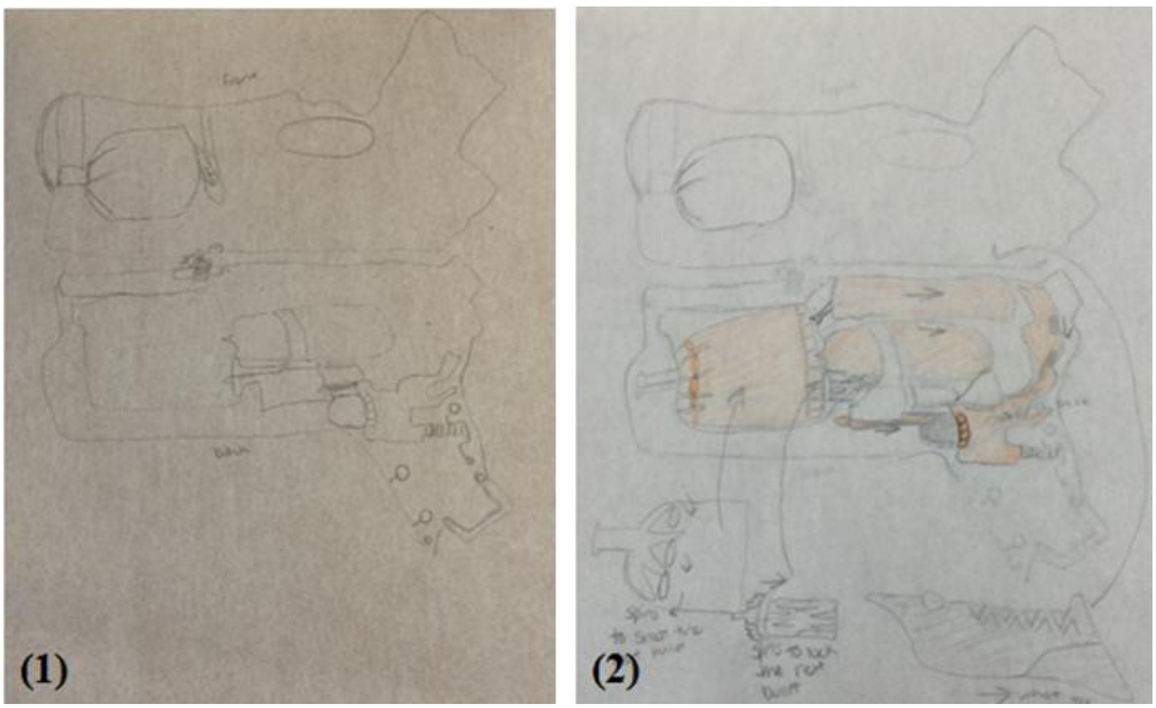

Figure 49. Student using color to show the different compartments of the blaster - (1) is initial blaster sketch, (2) is color overlay with additional component details.

Another student used color to highlight a connection between their sketch and their component tree (Figure 50) that they constructed as part of the activity.

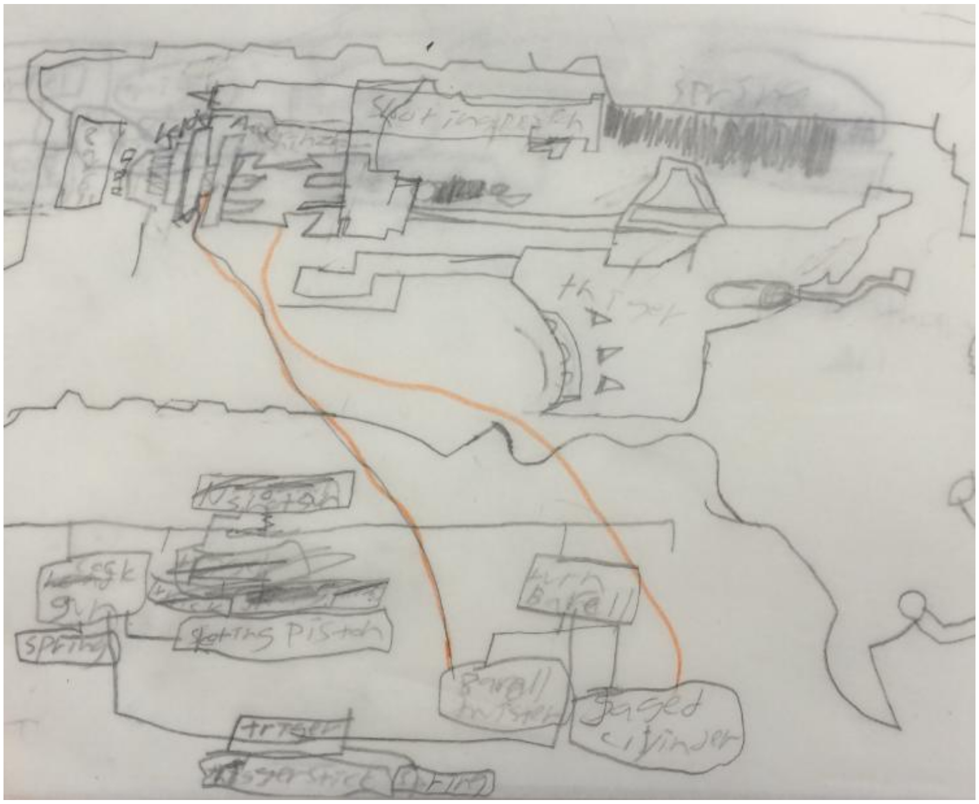

Figure 50. Using color to highlight identifying components.

The sketch that utilized the highest number of colors showed that the student chose the colors based on the actual colors of the NERF toy (Figure 51). Doing so added aesthetic appeal and differentiation between the various components.

Figure 51. Replicating the colors of the blaster and differentiating components.

Many of the participants used only a single page of paper for sketching the parts, such as what is shown in Figure 52. Interestingly, some of the students used some of the tips that were shared during the workshop to make connections between parts and the assembly (Figure 53) and show different views of some of the parts.

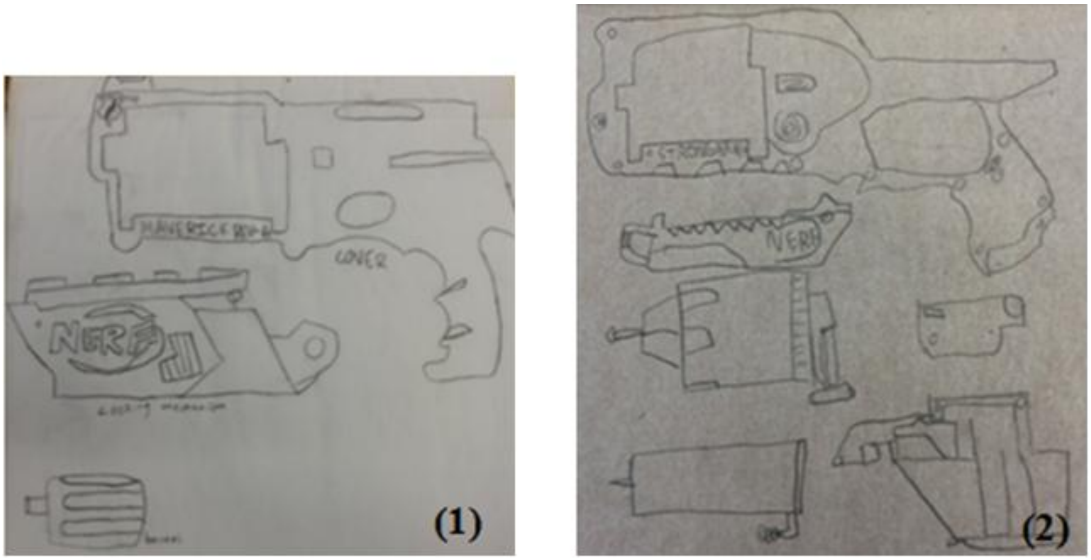

Figure 52. Sketching of individual components.

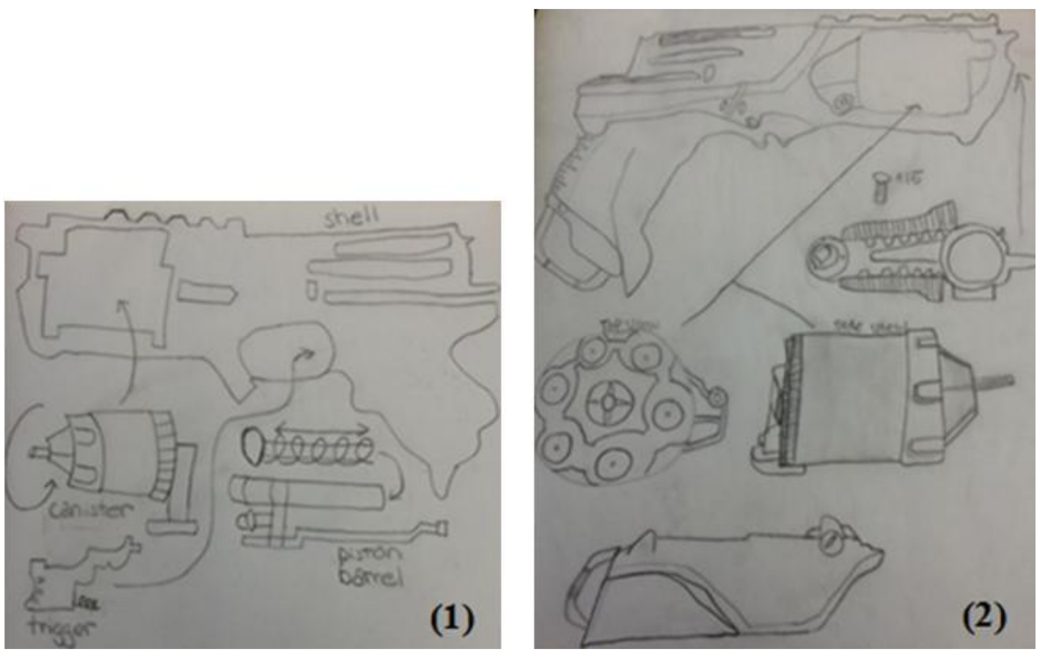

Figure 53. Sketching individual components but using arrows for exploded views.

For the post-survey, the kids were asked how many colors they used to sketch the components of the toy (see Table 3) and if using color was helpful. During the activity, it was observed that all children were sketching using at least a lead pencil. So, it is the assumption that those that answered that they used 0 colors meant that they did not use any colors in addition to their regular pencil.

Table 3. Number of colors used to sketch the NERF Blaster.

	Sketchbook Analysis	**Participant Post-Activity Survey Responses**
Number of colors used	**Number of users**	**Number of users**
0	0	3
1	14	10
2	2	1
3	0	2
4	1	0

The results, shown in Figure 54, reveal that the vast majority of the participants only used one color to sketch the NERF Blaster components. Four of them even clearly stated that their color of choice was "lead," implying pencil. The most common used color used, other than lead pencil, was orange.

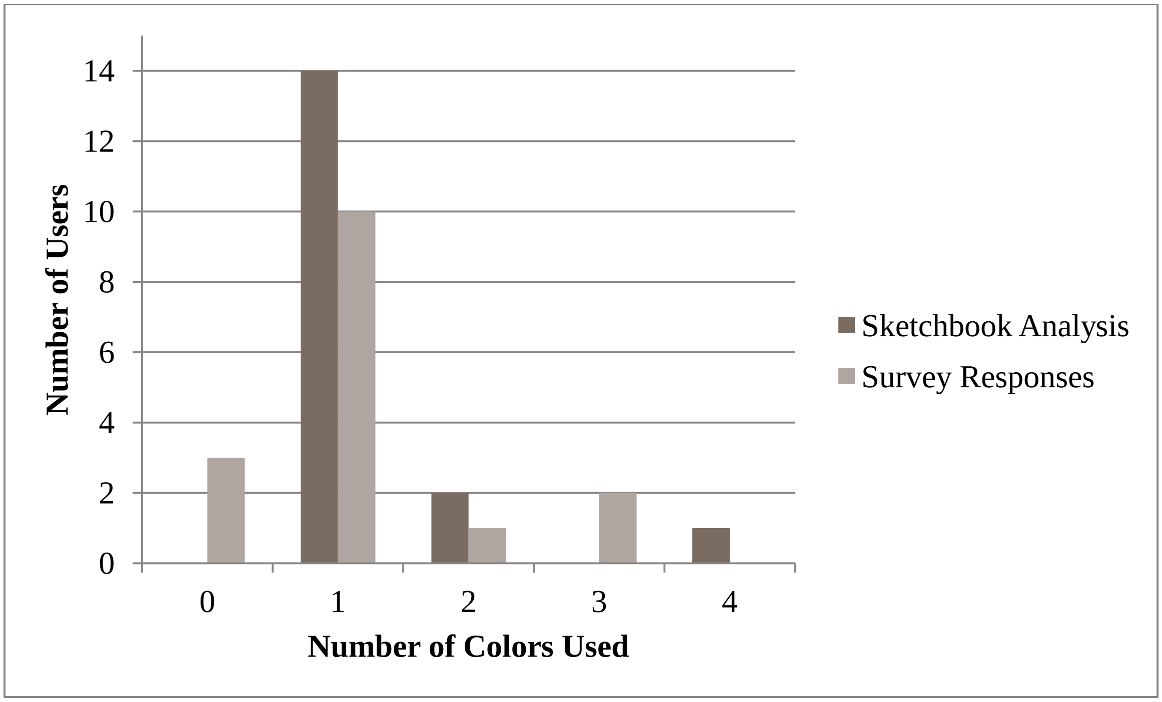

Figure 54. Number of colors used during sketching.

These results indicate that the majority of the children did not utilize color as a design tool. 9 participants had indicated that they planned to use color in sketching, but only 3 actually implemented color. These results did not correlate with the responses to how they felt using different colors for design during the sketching portion of the activity (Figure 55).

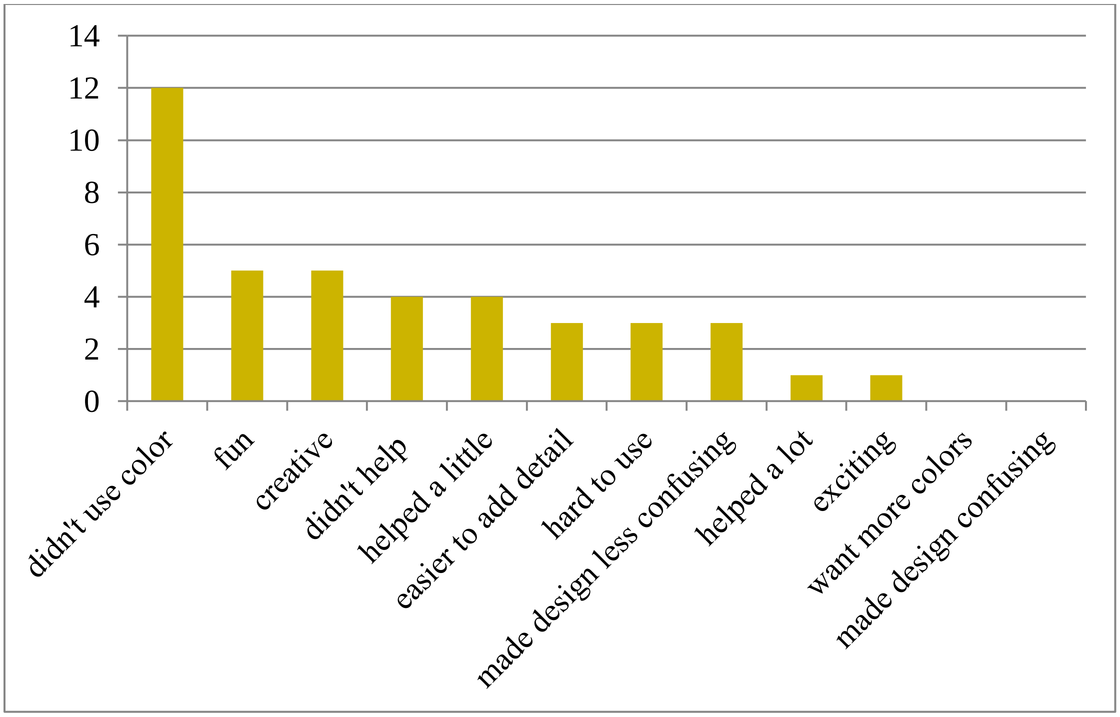

Figure 55. Describing use of color during sketching in the workshop.

The number of users indicating positive associations with using color, such as "fun" and "creative", were each more than the number of users that used at least 2 colors. This suggests that students may have been confused by the question and made the assumption that an answer of "1 color" meant that they used 1 additional color to standard pencil. Therefore, it is hard to differentiate between those that used 'colorful' colors and those that used standard colors, such as black and gray. In a separate question, 13 kids indicated that using color was not helpful while 3 indicated that it was. These responses are perplexing since only 3 children used color in their sketching.

CHAPTER 13. CONCLUSIONS AND FUTURE WORK

13.1 Conclusions

This longitudinal study offers some insight into how junior high age (12-14) children use sketching to communicate ideas. It was observed that the students were somewhat hesitant about using sketching at the beginning of the workshop. Their puzzled facial expressions suggested that they did not understand why an art-based method was being used in the workshop for tangible design activities. Analysis of the participant-surveys revealed that the students understood that sketching could be very important for design in terms of planning, visualization, and blueprinting; however, sketching was minimally utilized for iterating design during the workshop. It appeared that the students held ideas in their memory and quickly built their designs before they could forget; they did not realize that sketching could be used to mentally offload ideas. These findings do not correlate with the design thinking results in previous research studies (Martinez and Stager, 2013; Yang, 2009) that presented that sketching is fundamental to design thinking. Repeated use of sketching during future learning activities could be a possible solution to embedding the artful methodology into their figurative toolkit for thinking. Children do not know the rewards of sketching until they learn the techniques and reflect on applications for past design activities.

There were no collaborative sketches produced among the student teams. One explanation for this is that there was too much freedom given to the participants during the activities. A solution to study collaborative sketching would have been to implement a break-out session where iterative sketching amongst the group members was mandatory, similar to what was seen in (Shah et al., 2001).

Lecturing to them about the concepts and structure of sketching principles while instructing them to practice those concepts arbitrarily elicited very little engagement and enthusiasm during the Sketching Workshop. When they were given a concrete design goal of sketching a physical NERF Blaster components individually, the students were all more engaged in sketching. This suggests that children need a physical representation to visualize to be fully engaged in sketching for design. When minimal guidance was offered for various sketching techniques and tips, some of the students experimented with them.

The students, in general, did not use color as a means to facilitate design. This could, in part, be due to their age and the repetitive use of lead pencil that they are most likely used to in school. Younger children are more likely to use colors for design since coloring books and arts and crafts activities are common in their curriculum. However, the colors that were used showed a direct relation to the tangible object's colors. This suggests that colors, when used, are chosen based on real-world representations.

13.2 Future Work

An additional Summer 2016 GERI *Toy Design Lab in Mechanical Engineering* session is scheduled from which even more sketching data will be collected. The data collected from the Summer 2016 GERI Workshop will continue to be evaluated. The activities for the second session are being re-evaluated to further explore the insights that emerged for sketching during the first session. A major component of the future analysis will be reviewing all of the footage that was captured by the GoPro cameras during the workshops to establish any connections or insights that went unnoticed during real-time observation. After all of the results have been compiled and conclusions drawn for the two sessions, a collaborative full paper (with the support of the author) will be written about the workshop with a particular emphasis on sketching to be submitted for the 2017 Interaction Design and Children (IDC) Conference. The author will also support additional sketching publications while working jointly with on-campus representatives.

Further studies need to be conducted to evaluate the effectiveness of sketching by children during design activities. Additional studies would provide meaningful data points from which statistical conclusions could be drawn for the relatively unexplored learning space of sketching for design thinking in children. Items that need to be addressed by further studies include how to help children learn design in a broader sense and be motivated to use it, as well as how to make them want to sketch for design without being told to do so.

LIST OF REFERENCES

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Adams, E., and Dormans, J. *Game Mechanics: Advanced Game Design*. Berkeley, CA: New Riders, 2012. Print.

"Average Mathematics Scores of 4th-grade Students, by Education System: 2011." *Trends in International Mathematics and Science Study (TIMSS)*. National Center for Education Statistics, n.d. Web. 04 May 2016.

"Average Mathematics Scores of 8th-grade Students, by Education System: 2011." *Trends in International Mathematics and Science Study (TIMSS)*. National Center for Education Statistics, n.d. Web. 04 May 2016.

"Average Science Scores of 4th-grade Students, by Education System: 2011." *Trends in International Mathematics and Science Study (TIMSS)*. National Center for Education Statistics, n.d. Web. 04 May 2016.

"Average Science Scores of 8th-grade Students, by Education System: 2011." *Trends in International Mathematics and Science Study (TIMSS)*. National Center for Education Statistics, n.d. Web. 04 May 2016.

Boyatzis, C. J., and Varghese, R. "Children's Emotional Associations with Colors." *The Journal of Genetic Psychology*155.1 (1994): 77-85. Web.

Carson, P. P., and Carson, K. D. "Managing Creativity Enhancement through Goal-Setting and Feedback." *Journal of Creative Behavior* 27.1 (1993): 36-45. Web.

"Color TV to Teach Mathematics." *Science* 126.3282 (1957): 1060. Web.

Cross, C. T., Woods, T. A., Schweingruber, H. A. National Research Council . Committee on Early Childhood Mathematics, and Ebrary, Inc. *Mathematics Learning in Early Childhood Paths toward Excellence and Equity*. Washington, DC: National Academies, 2009. Print.

Cross, N., and Cross, A. C. "Winning by Design: The Methods of Gordon Murray, Racing Car Designer." *Design Studies*17.1 (1996): 91-107. Web.

Dickey, M. D. *Aesthetics and Design for Game-based Learning*. 2015. Print. Digital Games and Learning.

Elliot, A. J., and Maier, M. A. "Color and Psychological Functioning." *Current Directions in Psychological Science* 16.5 (2007): 250-54. Web.

Engelbrecht, K. *The Impact of Color on Learning*. Proc. of NeoCon, Chicago. Perkins & Will, 2003. Web.

Ferguson, E. S. *Engineering and the Mind's Eye*. Cambridge, Mass.: MIT, 1992. Print.

Fisher, K., Hirsh-Pasek, K., Golinkoff, R. M., Singer, D. G., Berk, L. "Playing around in School: Implications for Learning and Educational Policy" Oxford Handbooks Online. 2012-09-18. Oxford University Press.

Ginsburg, H. P. *Mathematical Play and Playful Mathematics: A Guide for Early Education.* 2006. Web.

Ginsburg, H. P. *Mathematics Education for Young Children: What It Is and How to Promote It. Social Policy Report. Volume 22, Number 1*. 2008. Print.

Goldschmidt, G. "The Dialects of Sketching." *Creativity Research Journal* 4.2 (1991): 123-43. Web.

Goldschmidt, G. "SERIAL SKETCHING: VISUAL PROBLEM SOLVING IN DESIGNING." *Cybernetics and Systems*23.2 (1992): 191- 219. Web.

Gross, M. D. "The Electronic Cocktail Napkin—a Computational Environment for Working with Design Diagrams." *Design Studies* 17.1 (1996): 53-69. Web.

Halverson, E. R., and Sheridan, K. M. "The Maker Movement in Education." *Harvard Educational Review* 84.4 (2014): 495-504. Web.

Hirst, B. "How Artists Overcome Creative Blocks." *Journal of Creative Behavior*26.2 (1992): 81-82. Web.

Honey, M., Kanter, D. E. *Design, Make, Play: Growing the Next Generation of STEM Innovators.* Hoboken: Taylor and Francis, 2013. Print.

Hsu, N. S., Kraemer, D. J. M., Oliver, R. T., Schlichting, M. L., Thompson-Schill, S. L. "Color, Context, and Cognitive Style: Variations in Color Knowledge Retrieval as a Function of Task and Subject Variables." 23.9 (2011): 2544-557. Web.

Jung, C. G., Hull, R. F. C., Adler, G. *The Archetypes and the Collective Unconscious*. Second ed. 1969. Print. Bollingen Ser. ; 20.

Kiili, K. "Digital Game-Based Learning: Towards an Experiential Gaming Model."*Internet and Higher Education* 8.1 (2005): 13-24. Web.

Kolodner, Wills. "Powers of Observation in Creative Design." *Design Studies* 17.4 (1996): 385-416. Web.

Kraemer, J., Craw, J. "Statistic of the Month: Engineering and Science Degree Attainment by Country." *Center on International Education Benchmarking: Learning from the World's High Performing Education Systems*. N.p., 27 May 2014. Web. 20 Nov. 2015.

Levine, S. C. *Early Puzzle Play: A Predictor of Preschoolers' Spatial Transformation Skill.* Vol. 48. 2012. Web.

Li, Z., Cheng, Y., Liu, C. "A Constructionism Framework for Designing Game-like Learning Systems: Its Effect on Different Learners."*British Journal of Educational Technology* 44.2 (2013): 208-24. Print.

Maltese, A. V., Melki, C. S., Wiebke, H. L. "The Nature of Experiences Responsible for the Generation and Maintenance of Interest in STEM." *Science Education* 98.6 (2014): 937-62. Web.

Martinez, S. L., Stager, G. *Invent to Learn: Making, Tinkering, and Engineering in the Classroom*. Torrance: Constructing Modern Knowledge, 2013. Print.

ME444 Toy Design: Computer Aided Design and Rapid Prototyping. Purdue University, n.d. Web. 16 May 2016.

Mehta, R., Zhu, R. "Juliet". "Blue or Red? Exploring the Effect of Color on Cognitive Task Performances.(REPORTS)(Author Abstract)." *Science* 323.5918 (2009): 1226. Web.

Miller, E., Almon, J. "CRISIS IN THE KINDERGARTEN: Why Children Need to Play in School." *The Education Digest* 75.1 (2009): 42-45. Web.

Moomaw, S. *Teaching STEM in the Early Years Activities for Integrating Science, Technology, Engineering, and Mathematics.*New York: Redleaf, 2013. Print.

Newcombe, N. S. "Picture This: Increasing Math and Science Learning by Improving Spatial Thinking." *American Educator* 34.2 (2010): 29-35. Web.

Olsen, J. *The Effect of Color on Conscious and Unconscious Cognition*. Thesis. Carnegie Mellon University, 2010. N.p.: n.p., n.d. Print.

Piaget, J. *The Construction of Reality in the Child*. New York: Basic, 1954. Print.

Pillias, C., Robert-Bouchard, R., Levieux, G., Jones, M., Palanque, P., Schmidt, A., and Grossman, T. "Designing Tangible Video Games: Lessons Learned from the Sifteo Cubes." *Human Factors in Computing Systems Proceedings of the SIGCHI Conference* (2014): 3163-166. Web.

Price, S. P., Falcão, T. P. "Designing for Physical-digital Correspondence in Tangible Learning Environments."*Proceedings of IDC 2009 - The 8th International Conference on Interaction Design and Children* (2009): 194-97. Web.

Purdue University. *2016 Summer Camps*. West Lafayette: Purdue U, 2016. *Gifted Education Resource Institute*. Web.

Resnick, M., Shneiderman, B., Fischer, G., Giaccardi, E., and Eisenberg, M. "All I Really Need to Know (about Creative Thinking) I Learned (by Studying How Children Learn) in Kindergarten." *Creativity & Cognition Proceedings of the 6th ACM SIGCHI Conference* (2007): 1-6. Web.

Revelle, G., Zuckerman, O., Druin, A., Bolas, M., Van Der Veer, G., Gale, C. "Tangible User Interfaces for Children." *Human Factors in Computing Systems CHI '05 Extended Abstracts* (2005): 2051-052. Web.

Schrage, M. *Serious Play : How the World's Best Companies Simulate to Innovate*. Boston, Mass.: Harvard Business School, 2000. Print.

"Science and Cognitive Development." *The Professional Development Program's Early Childhood Education and Training Program*. State University of New York Early Childhood and Training Program, n.d. Web. 21 Mar. 2016.

Shah, J. J., Vargas-Hernandez, N., Summers, J. D., and Kulkarni, S. "Collaborative Sketching (C-Sketch)--An Idea Generation Technique for Engineering Design." *Journal of Creative Behavior* 35.3 (2001): 168-98. Web.

Sorathia, K., Servidio, R. "Learning and Experience: Teaching Tangible Interaction & Edutainment." *Procedia - Social and Behavioral Sciences* 64 (2012): 265-74. Web.

National Research Council Staff, Kilpatrick, J., Swafford, J. *Helping Children Learn Mathematics*. Washington, US: National Academies Press, 2002. ProQuest ebrary.

Terrenghi, L., Kranz, M., Holleis, P., Schmidt, A. "A Cube to Learn: A Tangible User Interface for the Design of a Learning Appliance." *Personal and Ubiquitous Computing* 10.2 (2006): 153-58. Web.

United States. Congress. House. Committee on Science Technology. *STEM Education before High School Shaping Our Future Science, Technology, Engineering and Math Leaders of Tomorrow by Inspiring Our Children Today : Field Hearing before the Committee on Science and Technology, House of Representatives, One Hundred Tenth Congress, Second Session, May 12, 2008.*Washington: U.S. G.P.O., 2008. Web.

Van Houten, R., Rolider, A. "The Use of Color Mediation Techniques to Teach Number Identification and Single Digit Multiplication Problems to Children with Learning Problems." *Education and Treatment of Children* 13.3 (1990): 216-25. Print.

Verstijnen, I. M., Van Leeuwen, C., Goldschmidt, G., Hamel, R., Hennessey, J. M. "Sketching and Creative Discovery." *Design Studies* 19.4 (1998): 519-46. Web.

Wolfgang, C. H. *Block Play Performance among Preschoolers as a Predictor of Later School Achievement in Mathematics.* Vol. 15. 2001. Web.

Yang, M. C., Cham, J. G. "An Analysis of Sketching Skill and Its Role in Early Stage Engineering Design.(Author Abstract)." *Journal of Mechanical Design*129.5 (2007): 476. Web.

Yang, M. "Observations on Concept Generation and Sketching in Engineering Design." *Research in Engineering Design* 20.1 (2009): 1-11. Web.

Youell, B. "The Importance of Play and Playfulness." *European Journal of Psychotherapy & Counselling* 10.2 (2008): 121-29. Web.

Zeimbekis, J. "Color and Cognitive Penetrability." *Philosophical Studies* 165.1 (2013): 167-75. Web.

Zuckerman, O., Arida, S., Resnick, M., Van Der Veer, G., Gale, C., Kellogg, W., and Zhai, S. "Extending Tangible Interfaces for Education: Digital Montessori-inspired Manipulatives." *Human Factors in Computing Systems Proceedings of the SIGCHI Conference* (2005): 859-68. Web.

APPENDICES

Appendix A. Teacher Email Correspondences

The following interview questions were emailed to educators known to the author that specialize in younger children.

1. At what age do children start learning addition/subtraction?
2. What is their dexterity at this age?
3. What is the appropriate toy size range for them to tangibly interface with at this age?
4. Why would/will they want to stay engaged in a math game?
5. Are there any triggers that should be built in that would encourage play or engagement?
6. What is the typical process and timeline for children to embed mathematical skills?
7. Do you have any recommendations for increasing embodied/memory capability?
8. Do you feel that the toy is intuitive enough as-is or should detailed instructions be included?
9. Do you personally recommend typical schooling methods or a different approach? Please explain.
10. With the basis of the toy in mind, do you have any recommendations for games to implement that would assist in teaching mathematical skills?
11. What is your professional experience with regards to educating children?

The questions were sent out individually to each of the three teachers with responses received on the following days:

- Appendix A.1 Teacher Interview 1 (Brittney Spiller) : May 29, 2015
- Appendix A.2 Teacher Interview 2 (Jessica DeTar) : June 3, 2015
- Appendix A.3 Teacher Interview 3 (Janelle Strathman) : June 1, 2015

A.1. Teacher Interview 1

1. At what age do children start learning addition/subtraction?

   So we usually start teaching addition/subtraction in our kindergarten-prep class. These children are ages 4 to 5 (right before they go to kindergarten). Our preschoolers are still generally working on simple numerical concepts. Like understanding counting in order and what 3 versus 9 represents. That being said, some 3 year olds can do simple addition subtraction and sometimes it takes them a bit to catch on to the concept.

2. What is their dexterity at this age?

   Around 3 they can trace straight lines and shapes, and are honing in on their fine motor skills. At 4 they can use scissor to cut circles and squares, connect dots, dress themselves without much help. At 5 they have greatly improved dexterity from age 3. Grip and grasp should be strong, they have a dominant hand by then, etc. If you want to know more information about this let me know...

3. What is the appropriate toy size range for them to tangibly interface with at this age?

   This can go either way. I say this because usually activities or toys end up working on multiple things; beyond the original purpose or the concrete way us adults think a toy or activity should work. Small toy size range also allows focus on developing small motor skills with fingers, wrists, and engaging different arm movement versus a large size range. Two year olds these days can manipulate and explore with iPhones, iPods, iPads, etc...and they only get better with age if that helps you to visualize.

4. Why would/will they want to stay engaged in a math game?

   Younger children love learning if their parents/teachers show that they love learning. They also are really in to displaying their knowledge. If they can be successful and show their accomplishments, they are more than likely to remain engaged. A math game would also need to teeter between being easy enough for them to feel like they can be successful, but also challenging enough to that it isn't a "baby game". Something extremely challenging could discourage the child from wanting to play the game as well...

5. Are there any triggers that should be built in that would encourage play or engagement?

   Bright colors, lights, music...these things all catch their attention. If you successfully complete the problem OR beat a level of the game and lights go crazy or a sound plays, they will try to make it happen again. This starts in infancy and continues up until adulthood. Let's be honest...we feel excited when we beat something and a song plays :)

6. What is the typical process and timeline for children to embed mathematical skills?

   With our early childhood students, we start math in infancy. Now this is along the lines of introduction to very basic concepts. Such as simple counting (1,2, 3) or sorting shapes (squares v. circles). As they get older we are constantly building on that foundation. Usually at two they can count from 1 to 3, on average. Some can go MUCH higher. I had an 18 month old count to 20 for me. From 2 on they should firmly understand shapes and recognize big v. small. Those spatial mathematical concepts. At 3 they begin to really dive into numerical understanding...1 is small than 5, counting 1,2,3 or by 2's (2, 4, 6). Once that is established, then they can begin doing simple addition and subtraction. Adding and subtracting can't be successful if they don't understand the numerical value of 1 versus 4. Our 5 year olds tend to do better, but we often begin introducing the idea at 4.

7. Do you have any recommendations for increasing embodied/memory capability?

   Keeping it fun but simple. Educational based toys are great but sometimes the idea can be overwhelming, which is not the goal if you want the child to be interested and use it

8. Do you feel that the toy is intuitive enough as-is or should detailed instructions be included?

   Always use detailed instructions, not because the concept is necessarily to difficult to grasp, but in my experience...parents aren't that bright :D

9. Do you personally recommend typical schooling methods or a different approach? Please explain.

   So, where I work, we do our curriculum based on an Emergent/Reggio style. We still do lesson plans etc, however, instead of the teachers coming up with a cookie-cutter lesson plan, they are to go off what the children are interested in. For example, if they are showing interest in dinosaurs then for the next week we will read books about dinosaurs, make dinosaur art, listen to songs about dinosaurs/do a dinosaur dance, set up a fossil digging Science activity etc. This also means we try to make more natural environments in the classrooms and encourage our families to be extremely involved in their child's learning. This schooling method is supposed to support a child's natural curiosity and support them intellectually as well as creatively. Reggio supports creative learning instead of providing them with a cookie-cutter approach/answer. I like that it lets our children be children and it keeps the learning fun. Many people also like Montessori. More often than not I see a lot of combined Reggio/Montessori. Taking a little from each style.

10. With the basis of the toy in mind, do you have any recommendations for games to implement that would assist in teaching mathematical skills?

    No. I think getting creative with the games and going outside of the box. As a adults we become so concrete and think that things have to be a certain way. So getting in touch with your inner child could help...or hell, ask some actual children what would make math fun. Kids are REALLY honest when you ask them a question!

11. What is your professional experience with regards to educating children?

    My educational background is in Speech Language Pathology and Psychology (minor), in which I have a Master's degree in. I worked with children, doing developmental therapy in hospitals and school settings. In the schools we focused on their developmental needs and the children's curricular needs within a therapy classroom. Which means, they were in this special classroom learning their core classes (math, science, reading, etc) unless they performed strongly in a subject, in which we would push them into a standard classroom for that lesson. Currently I work as a team lead in an early childhood education setting. I lead the infant and toddler teachers (ages 10 weeks to 24 months) in curriculum and environmental set ups. I also occasionally help our twos through kindergarten prep classes with curriculum.

A.2. Teacher Interview 2

1. At what age do children start learning addition/subtraction?

   The answer to this question is Kindergarten, 5 and 6 years of age.

   - Preschool - Kids understand that the written number "3" represents three objects (teddy bears, for instance.)
   - (By the end of) Kindergarten - memorize, recognize numbers up to 20 (ideally to 50) with automaticity. Simple word problems are introduced, "Belle has 5 animal crackers and eats 2, how many does she have left?" and then from there the numerical signs are used 5-2=3
   - (By the end of) First Grade - kids should know how to add and subtract numbers easily and with automaticity up to 20 using paper and/or counters, and also add and subtract multiples of 10 in their head. Maybe multiples of 5 if they're good!

2. What is their dexterity at this age?

   My understanding of dexterity is how a child responds to toys and how he plays with them. In kindergarten, children are beginning to use their fine motor skills every day, and we aid them in developing these skills with drawing lines, shapes, letters, numbers, cutting different kinds of paper, placing small items using sorting and simple movement through games and artistic ability. Children at the age of 5 and 6 should be able to easily transfer items from one hand to another, stack items, place items in a simple pattern (i.e. ABAB, ABC, ABB, ABCD, with no more than 4 repeating items.)

3. What is the appropriate toy size range for them to tangibly interface with at this age?

   I am thinking LEGO duplo blocks, but there is no longer any danger of choking or kids putting things in their mouth at this age, with normal development they should be past that for sure. Something marginally smaller than LEGO duplo blocks would be ok, but not too much smaller than than that, lest they lose it. Don't go as small as normal small LEGO blocks. That's too small.

4. Why would/will they want to stay engaged in a math game?

   Kids at age 5 and 6 have attention spans that range from a few seconds to 15 minutes. It depends on many factors, but I would say that 15 minutes is the absolute maximum.

5. Are there any triggers that should be built in that would encourage play or engagement?

   Bright colors, sounds, flashing lights.

6. What is the typical process and timeline for children to embed mathematical skills?

   See above.

7. Do you have any recommendations for increasing embodied/memory capability?

   No, I'll leave you to that! One thing I will mention is that in teaching I constantly consider the ZPD (Zone of Proximal Development) and the scaffolding technique. Basically scaffolding is

   a. Understanding what the child can already do independently = Independent Level

b. Understanding what the targeted level of performance is (usually this is something the child has no idea how to do on his own) = Frustration Level

c. Figure out how to get the child from the Independent Level to eventually accomplish what is desired in # 2, the Frustration Level. The way to do this is to work within that middle level, which we call the ZPD (Zone of Proximal Development.)

See this website for a more detailed explanation http://www.simplypsychology.org/Zone-of-Proximal-Development.html

8. Do you feel that the toy is intuitive enough as-is or should detailed instructions be included?

I personally have taken several days to consider what you are describing, and, while I understand where you are trying to go, I am stymied about how you are going to get there. I think that detailed instructions are always a vital part to anything, but I'm one of those dorks who reads all directions and keeps the manuals for future reference in a filing system. So...

9. Do you personally recommend typical schooling methods or a different approach? Please explain.

There are so many different ways to teach and so many ways kids learn, but what you are describing is a kinesthetic approach with a technological component, which perfectly plays into the way this generation of kids think and learn! This toy does not strike me as typical schooling methods because it is personalized and instantaneously responsive. Typical schooling methods usually go like this:

- Introduce the concept to be taught/activate prior knowledge/get the kids hooked on why this is important by connecting it to their world
- Instruction - This is the part where there are many different methods teachers employ.
- Guided Practice - The teacher helps the students, with a lot of support, to accomplish the desired goal.
- Independent Practice - The student is expected to demonstrate the desired skill and the teacher reviews the work to understand how well the concept was grasped.
- Assessment - After multiple lessons, the student is expected to have understood the concept and can complete a graded assessment with (hopefully) at least 75% accuracy.

10. With the basis of the toy in mind, do you have any recommendations for games to implement that would assist in teaching mathematical skills?

    What if the kid fails repeatedly? What kind of reteaching could go on? If the toy is too difficult to manipulate, kids will lose interest and parents will want money back. :/

11. What is your professional experience with regards to educating children?

    I have a Bachelor's Degree of Science in Education from May of 2010 at Missouri State University in Springfield, Missouri. My certification is Kindergarten-6th grade in the state of Kansas. My professional experience is as follows:

    - 2 years teaching kindergarten

- 1 year teaching preschool
- 2 years teaching third grade

A.3. Teacher Interview 3

1. At what age do children start learning addition/subtraction?

   Very basic addition and subtraction starts in kindergarten. However, when adding and subtracting at this age, kids need to be able to see tangible objects. These kids need a visual representation of 3+2 such as a the number 3 with three apples underneath it, and the number 2 with two apples underneath it. As they are adding the apples together, the kids are taught to actually touch the apples.

2. What is their dexterity at this age?

   At the kindergarten age (5-7 years old), they are able to firmly grasp small objects. They are able to understand and mimic patterns. They are able to push buttons with their finger or the palm of their hand. They have a decent handle on fine motor skills, coloring, writing, buttoning large buttons, and manipulating a zipper.

3. What is the appropriate toy size range for them to tangibly interface with at this age?

   If only hitting one button or light, I believe a 2inch by 2 inch surface should suffice. If they are needing to toggle between different screens, then something the size of an average iPad would be necessary.

4. Why would/will they want to stay engaged in a math game?

   The best thing to keep children engaged at this level are songs, movement, lights. Anything to get them up and moving keeps them engaged to their fullest potential.

5. Are there any triggers that should be built in that would encourage play or engagement?

    If there were a way to include sound, that would help (but probably drive the teacher/parent crazy haha). If you could also include a vibrating sensation that differs if they get an answer right or wrong would help to keep their attention.

6. What is the typical process and timeline for children to embed mathematical skills?

    This is hard to answer. You're basically asking how long does it take kids to learn math, and there is no answer for that. Obviously with anything, some kids pick it up quicker than others. Yes, schools and state standards have set time lines for when students should master certain skills, but again it's totally different for each kid.

7. Do you have any recommendations for increasing embodied/memory capability?

    Repeat, repeat, repeat. At this age, they pick up on things easier, and if you tie it to music, it somehow tends to stick better than other things. Why do you think little kid shows sing-song everything, it helps kids remember information.

8. Do you feel that the toy is intuitive enough as-is or should detailed instructions be included?

    I definitely think detailed instructions wouldn't hurt. It's always better to give too many instructions than too little. This could be something that the kids play with together during Math centers time or siblings to be playing with together. You'll have a very wide range of audience.

9. Do you personally recommend typical schooling methods or a different approach? Please explain.

   I could see this being used in a school setting, but not by a teacher and student one-on-one, that's just not practical. If there were a way for a teacher to have a 'master block' and all of the students have the other blocks and the teacher could assess all of the students at the same time that would be beneficial. However, I see this most likely used as a Math center activity for students to do with their peers. I can also see this in a special education or remedial math setting, where there is the availability for more one-on-one time between the teacher and the student. I can also see this being used with parents who work with their students at home, as well as parents who homeschool, again, it works best in an environment where one-on-one is available.

10. With the basis of the toy in mind, do you have any recommendations for games to implement that would assist in teaching mathematical skills?

    I'll be honest, I'm not entirely sure what you're asking.

11. What is your professional experience with regards to educating children?

    I have my bachelors degree in Elementary Education with an area of concentration in Special Education. I am certified to teach Special Education students from grades K-12 and I am certified to teach students in the regular education setting in grades 1st-6th. I also have my masters in Elementary

Administration. I have taught 6th grade Special Education for 1 year and 5th grade regular ed. for 3 years.

Appendix B. GERI Activity Sheets

B.1. Marshmallow Tower Challenge

Toy Design

Marshmallow Tower Challenge

Overview

Type: Small group

Goal: Create the tallest tower possible that can balance a marshmallow on top.

Time: 20 mins

Materials:

- 20 sticks of spaghetti
- 1 yard of tape
- 1 yard of string
- 1 jumbo marshmallow

Notes: The height of the tower will be measured from the bottom of the marshmallow to the ground.

Learning Outcome

Topic: Statics

At the completion of the activity the students will be able to:

- Understand tension, compression and bending
- Know about the distribution of forces
- Visualize the stability of the structure and loads acting on a stationary body.
- Uses and properties of shapes
- Have a better bond with members of the team

Preparation

- Distribute materials for each team (see materials list)
- Have post it pads on each table (X 4)
- Gather markers, pencils, and paper for each student
- Create/print the marshmallow tower pre and post survey for each student

Toy Design

Procedure

Total time: 1 hr

• **Introduce the marshmallow tower challenge**	**2 mins**
• **Pre survey**	**5 mins**
• **Students complete challenge**	**25 mins**
• **Explanation**	**20 mins**
• **Post survey**	**8 mins**

Introduction

For this activity, you will be building a tower out of only spaghetti, tape, and string. You want to make the tower as tall as possible but it must be able to support a jumbo marshmallow. The height of your tower will be measured from the table to the bottom of the marshmallow. Any additional structure above the marshmallow will not count.

During Challenge

Take photos of each tower iteration the students build. Try to take photos from the same angle(s) every time.

Explanation

See marshmallow tower powerpoint presentation.

Website

http://www.pbs.org/wgbh/buildingbig/lab/shapes.html

Toy Design

Pre-Assessment

1. Sketch the idea for your tower.

2. What are your design goals??

3. Are there any physics concepts that you learned in school that will be useful for this project?

4. On a scale from 1 to 10, how complex do you think the idea for your tower design is?

5. Why is sketching important for design?

Toy Design

Reflections

1. Sketch the model of the tower that your team created. If you created multiple designs, sketch the one that worked best.

2. What are some of the connections between this project and the concepts you have learned in science or physics class?

3. While designing your team's marshmallow tower, have you had to make any changes? What changes were made to your design? How many iterations did you go through?

4. On a scale from 1 to 10, how would you rate your final product in terms of achieving your design goals? Why?

5. Given more time, what would you do to improve your design and making to achieve your design goals?

6. If you were going to teach your friends at school about what you have learned today, what are the most important things you would want to tell them?

Toy Design

7. Did sketching help you with designing your tower? Please explain.

8. Please circle all of the words that describe the sketching portion of the challenge:

Boring	Fun	Working together
Easy	Challenging	Hard
Creative	Interesting	Finding solutions
Working by myself	Worthwhile	Pointless
Exciting	Messy	New ideas

B.2. Sketching Workshop

Toy Design

Sketching for Design

Overview

Introduction to the nature of sketching and the basic tools for 2D sketching, importance of annotations and good posture.

Learning Outcome

By the end of this activity students will:

- Be able to communicate their ideas thru sketches easily
- Not have inhibitions for sketching
- Have a good tool in brainstorming
- Will be able to differentiate between sketching and drawing
- Will know what is a good posture for sketching practices
- Know the importance of annotations and markings on sketches and drawings
- Be able to draw easy 3d sketches. (optional)

Preparation

- Design notebook for all students
- Water color pencils for all students
- Sharpeners
- Crayons
- Finger paints

Procedure

Total time :1 hr 30 mins

• Activities to remove inhibition • Introduce to sketching Difference between sketching and drawing	10mins 10 mins
Draw a straight line Draw a circle	10 mins
• Introduction to good posture • Some more activities to remove inhibition	5 mins 10 mins
• Line-weights	10 mins
• annotations	10 mins
• Giving scale	10 mins
• Showing motion: use arrows and symbols • Boolean combinations • Draw jack in a box	10 mins 5 mins

Toy Design

Sketching: Pre-Assessment

1. Do you tend to think in words or pictures?

2. Effectively communicate how a Jack-in-the-Box works

3. When explaining your ideas to others do you prefer sketching or verbal communication? If someone was explaining their idea to you, which would you prefer? Why?

4. What is the difference between a drawing and a sketch?

5. Do you think a sketch can effectively communicate a design on its own without any additional explanation? Why or why not?

6. What color do you prefer in sketching? Why?

Toy Design

Reflection

- **Which part of sketching do you think is the *__easiest__*? Please circle only one.**

Shading	Giving scale	Drawing initial shapes
Thinking of what to draw	Thinking of how to draw it	Connecting the shapes
Adding features, details	Outlining	Showing motion

- **Which part of sketching do you think is the *__hardest__*? Please circle only one.**

Shading	Giving scale	Drawing initial shapes
Thinking of what to draw	Thinking of how to draw it	Connecting the shapes
Adding features, details	Outlining	Showing motion

B.3. NERF Blaster Challenge

Toy Design

Nerf blaster challenge

Overview

Type: Individual

Goal: Disassemble a NERF blaster to understand the individual components and how they work together to form mechanisms. Sketch all components and annotate the parts. Reassemble the NERF blaster correctly and shoot a target.

Time: 2 hours

Materials:

- NERF blaster for each student (x17)
- Screwdrivers for each student (x17)
- Pencils and sketch pens (multiple colors)
- Poster pads

Notes: Encourage students to think about how the parts were manufactured. During reassembly, first person to shoot their NERF blaster and hit the target wins.

Learning Outcome

Topics: Sketching, Mechanisms, Manufacturing

By the end of this activity students will:

- Sketch a NERF blaster and understand how it works
- Differentiate the individual components of the NERF blaster and understand the mechanisms involved with each
- Be introduced to various mechanisms and their real world applications
- Be introduced to different manufacturing techniques: Injection molding & wire bending
- Define reverse engineering as the process of disassembly and careful analysis with the goal of duplicating or improving a device or component.

Preparation

- Distribute screw drivers and NERF blasters for each student (x17)
- Drawing utensils (pencils, sketch pens)
- Poster-pads

- Tracing pads(x17)

Procedure

Total time: 3 hrs

Warm up: Brain teasers	5 mins
What is reverse engineering? Introduction to nerf blaster How to use the screw Driver	10 mins
Pre-survey	5 mins
Disassemble the Nerf blaster	45 mins
Break	10 mins
Sketching different parts of the Nerf blaster and name	30 mins
Post survey	5 mins
Introduction to mechanism	20 mins
Assemble and test the NERF blaster	30 mins
Shoot and Play	10 mins

Brain Teasers

Draw the isometric View of the figures

Front view

Top View

Toy Design

What is reverse engineering?

Reverse engineering is the disassemble of another manufacturers component to see and understand what it does and reproduction of the system or improve on the existing system to build your own engineering product.

We can understand a lot by studying the existing product. By knowing how the machine works we can improve its design or use the principles at other areas to come up with our own way of developing new products.

Reverse engineering, however, is not simply taking something apart. This process requires careful observation, disassembly, documentation, analysis and reporting. Many times, the reverse engineering process is *non-destructive*. This means that the object or component can be reassembled and still function just as it did before you took it apart.

Introduction to NERF

See powerpoint. Stop at slide #10. Introduction to functions and function trees? Are we including this?

-Students disassemble NERF blaster-

Slides 10-13 : Function trees

Sketching parts:

Slides 14-15. Name the parts.

Nerf Blaster: Pre-Assessment

1. What do you think reverse engineering means?

2. What do you think throws the Dart forward? Explain with sketch.

3. What do you think is more painful, getting hit suddenly or applying the same pressure over a certain period of time? Why?

4. How do you think the shell of the blaster was made? (How does it go from pure plastic to the final product?)

5. Do you think it would be difficult to sketch each of the components?

6. Do you think you will use any other colors to sketch the NERF Blaster? If so, why?

7. If you were going to use a color to sketch the "air" trailing behind a NERF foam arrow, what color would you use? Why?

Toy Design

Nerf Blaster: Reflection

1. What throws the dart forward? Explain with a quick sketch.

2. What does the device do? What part makes it work this way?

3. How does the blaster stay in the cocked position? How is it fired when you press the trigger?

4. Explain how the barrel holding the darts rotates after each fire.

5. How would you improve the way the device was made?

6. Can you redesign this device to make it function differently? How would you do this?

Toy Design

7. How many colors did you use to sketch the toy?

8. Did color help you with the sketching exercise? If so, why/how?

9. Please circle all of the words/phrases below that describe how you felt using different colors for design during the sketching portion of the activity:

Fun	Didn't help	Creative
Helped a lot	Easier to add detail	Helped a little
Didn't use color	Made design confusing	Hard to use
Want more colors	Exciting	Made design less confusing

10. If you were going to teach your friends at school about what you have learned today, what are the most important things you would want to tell them?