Playful Calculation: Tangible Coding for Visual Calculation

by

Derek Ham

Bachelor of Architecture, Hampton University, 2001
Masters of Architecture, Harvard Graduate School of Design, 2003

Submitted to the Department of Architecture in
Partial Fulfillment of the Requirements for the degree of

DOCTOR OF PHILOSOPHY IN ARCHITECTURE:
DESIGN AND COMPUTATION

at the
Massachusetts Institute of Technology
June 2015

Signature of Author: Signature redacted
Department of Architecture
May 1, 2015

Certified by: Signature redacted
George Stiny
Professor of Design and Computation
Massachusetts Institute of Technology
Thesis Advisor

Accepted by: Signature redacted
Takehiko Nagakura
Associate Professor of Design and Computation
Massachusetts Institute of Technology
Chair, Department Committee on Graduate Students

Dissertation Committee

George Stiny
Professor of Design and Computation
Massachusetts Institute of Technology
Advisor

Edith K. Ackermann
Professor of Developmental Psychology
University of Aix-Marseille, France
Visiting Scientist
Massachusetts Institute of Technology Design Lab
Reader

Erik Klopfer

Professor of Science Education and Engineering Systems
Director of MIT Scheller Teacher Education Program (STEP)
Massachusetts Institute of Technology
Reader

Playful Calculation: Tangible Coding for Visual Calculation

by

Derek Ham

Submitted to the Department of Architecture on
May 1, 2015 Partial Fulfillment of the
Requirements for the degree of Doctor of Philosophy
in Architecture: Design and Computation

ABSTRACT

Play and calculation are often considered to be at odds. Play embraces the wildness of youth, imagination, and a sense of freedom. Calculation, to most, represents rigor, mechanistic behavior, and following inflexible rules. This work seeks to challenge these notions by putting play and calculation together. Design activities are one such place where individuals can be playful with the rigor and firmness of calculation. Shape grammars demonstrate this most eloquently by providing a playful system of design inquiry based on rules and schemas. Through embedding and shape emergence, designers can enter into a state of play or what Huizinga calls the "magic circle." It is in this magic circle that we also find Caillois's categories of play: alea, agôn, mimicry, and ilinx. The culmination of these activities found in the design process is what I call "playful calculation."

In this research, I have developed a visual calculation game based on the principles of shape grammars. This game serves as a precedent for ways to teach design in schools of art and architecture; it also serves as a device to instruct young children (K-12) on rule based designed processes. This dissertation includes the findings of a five-month study conducted at the Boston Children's Museum. In the spirit of Piaget and Vygotsky, I use play to analyze the behavior of young children and to see how they creatively interact with materials. The children did the expected and the unexpected, giving insight into ways we can teach the arts and design.

This body of work provides a fresh take on design and STEAM (Science, Technology, Engineering, Arts, and Math) education. Most promoters of the STEAM movement suggest adding the arts to an already packed STEM curriculum. This study views the arts (and design) as having the same rigor and basis in calculation as STEM fields. In fact, there are many ways to calculate, and visual calculation with shape grammars is the key to this understanding. In this research, I bring shape grammars into the discussion of K-12 education reform. With shape grammars we find a brand new lens to view art and design education through playful interaction.

Thesis Supervisor: George Stiny
Title: Professor of Design and Computation

Acknowledgments

First, I would like to thank my doctoral committee: Edith Ackermann, Erik Klopfer, and George Stiny. George, it has been a great privilege working with you; thank you for shape grammars.

Additionally, I would like to thank the design computation faculty (Takehiko Nagakura, Terry Knight, and Larry Sass) for all of your support and feedback on my work. A special thank you must go to Larry Sass, who has been a wonderful mentor during my time at MIT.

I would like to thank my colleagues and friends in Design Computation; your feedback and discourse along this journey have greatly impacted this work. I am happy that we created a new synergy around computation and design education!

I thank my UROP, Rosa Manzo for her collaboration as a researcher at the Boston Children's Museum. I would like to thank Maria Alessandra Segantini, Justin, and the other members of the Venice, Italy design studio at MIT School of Architecture + Planning who helped me with my ethnographic study.

I thank Graham Jones, Kieran Downes, and my fellow classmates in the 21A.760/15.349J Qualitative Research Methods course for your invaluable feedback for this methods project.

Finally, I must thank my family! My parents, Gary and Harriet Ham, and mother, Mary Woodard, have been an active part of this journey with your prayers and support. I'd like to recognize my children. To my daughter Taylor, you helped me discover the shape game, and Reid, I have enjoyed seeing the world through your eyes as you play. To my wife, Remi, your support has been the greatest of all. I could not have completed this journey without your love, support, critical feedback, and listening ears. Thank you for being my number one cheerleader.

Like Frobel, I too am a follower of Jesus Christ; I believe that with God nothing is impossible.

Table of Contents

List of Figures

Preface

When people ask me what my research is about, I tell them it's a lot like cooking. When you cook, you don't just throw a bunch of ingredients in a pot; you often follow a recipe. However, creating a recipe and cooking are two separate activities. The latter may be a step in the preparation of the former. Also, cooking may be tooled with in formulating a recipe. But for my purposes here—to more fully explain what my research is about—let's look at recipe creation.

First, recipe creation requires the usage of words and symbols to convey the steps necessary to prepare a particular dish. These steps have to be precise, providing exact instruction on how to use and what to do with the ingredients. They might include the sequence of actions needed to cook the ingredients and, in some cases, the actual equipment used to do the cooking. All of this can be a lot to remember, even for the most skilled chef, so it helps to write down the recipe. At the same time, experienced chefs follow recipes loosely, at best. The recipes serve as guides from which chefs improvise, make changes, and rewrite.

For many years, design educators have been teaching students either to cook up their designs without recipes or to follow recipes. We have not shown the method of creating a recipe or focused on the skill set to reengineer a recipe after tasting someone else's design. Of course, some would call taking ideas from taste testing another's design an act of cheating, but in the culinary world, swapping flavors is at the core of artistic expression. Any great chef learns that there is some room for improving or changing a recipe. It offers such flexibility. Once the recipe is mastered, the chef then can add something new to it or maybe swap ingredients, all the while playing and experimenting during the creation and/or cooking process. Nonetheless, the recipe is always present.

Comparing recipe creation in the culinary world to that of design begs the question: *Why not do this in design?*

Algorithms are nothing more than recipes, and I believe it is time for designers to start learning to play with them. Creating a design recipe is just as playful as the actual process of building or fabricating a design. Furthermore, recipes can be created —and tweaked—before, after, or during the cooking process. We can use them to cook or as a way to analyze what we have tasted. It's a great metaphor to think about design and a helpful way to think about the intersection of creativity and calculation.

Another one of my favorite examples to talk about my work is the metaphor of music and learning to play an instrument. As a novice pianist, I do what most call "playing by ear." Playing by ear is not the same thing as being self-taught. One can be taught to play via music reading or by ear. Being self-taught, of course, means someone learns without the instruction of another. As a child I took formal piano lessons (for a short period of time) before focusing on the trumpet, which I played through middle school and high school. Learning to play the piano was intimidating for me because of the classical way in which it was taught. I could easily identify and play every note on the piano keys, but as soon as I was presented with reading music on paper, I could not transfer the signs on the paper back to my hands. So, for a time, I quit.

When I was older, I took to the piano again, but this time I abandoned the notes on the page and went directly to the "playing by ear" method of learning. To do this, I learned how to play songs I liked by slowly learning to copy music I listened to from a CD or radio. I spent hours and days doing this until I would "learn a song" and then would proceed to another. Eventually, I began to see the similarities in songs in the way they were structured and the way my hands played the keys. Once I became comfortable playing a song exactly as I heard it, I began to improvise by playing it differently or by mixing new melodies into the piece in the same key. This type of learning was much more intuitive for me. It also conveys a lot about how I think about play and learning. Like most people, I picked up my piano playing through informal learning.

It has been said that most people learn 75% of what they know through informal learning (Cross, 2007). Informal learning by definition is not done in traditional learning environments; it often stems from the interest of the learner. In fact, when we begin to look at what qualifies as "informal learning," we discover the conditions we need for play to occur are characterized by it. The challenge for educators, then, is to create ways in which their students can tap into this modality of learning in the formal setting of a classroom.

This thesis will look at play as an informal learning method to teach design. It will discuss how we can utilize games and play to teach design and creativity. It also covers new ways in which we can evaluate games and play activities from the standpoint of calculation. Finally, it will challenge educators to think about their own practice as a playful activity, to show that even in creating curricula and learning environments we can use playful calculation.

Chapter 1

Introduction

The subject of play is most often misunderstood by those who believe they have outgrown its usefulness. In the domain of child psychology and primary education, the subject of play is situated under critical discourse as it often provides the most telling story of the human condition. What we see in play can tell us a great deal about how we learn, how we socialize, and most important to this research, how we are creative.

The major discussions about play's impact on K-12 learning have centered on three major arguments: the first that play helps children with social development; the second that play helps with formal education readiness and academic gain; and finally that play increases engagement and agency in the classroom. While these are definitely great outcomes from the impact play has on learning, I would like to expand this inquiry and talk about play's ability to strengthen an individual's ability to calculate. When I use the term "calculate," I am not solely talking about mathematics. I want to talk about calculation in the way George Stiny talks about it. In his work *Shape* (2006), he states there is the *"mathematics for design and the special mathematics of design"* (p. 11). This is where I want to situate the conversation on play, learning, design, and calculation. Play is a conduit to get designers to use rules, develop schemas, and embed to find emergent structures. In fact, play is calculation.

The words "play" and "calculating" hold such powerful preconceived notions that most often the two subjects are placed in different worlds. While many would agree that design is inclusive of acts of calculation, most would reject calculating as a working definition for the entire design process. For the statement to be true, we must do two things: expand our understanding of what it means to calculate and, secondly, classify the activities that define design-play.

Architecture and design education is not without opportunities for students to learn through play. Most design methods begin with some element of play through the game of "seeing with the eye." Others might argue that play is involved from the initial process of creating things with your hands, building models, or even drawing. And then there are those who might say play is involved when they imagine themselves inside their spaces looking at a scaled model or digital walkthrough on their computer screen. All of these are true, but I would like to show that this is not the full story of a designer's play experience. Play allows us to calculate in very intuitive ways. It provides for moments of reflection and for moments of whimsical imagination. It is the key to being creative.

Playfulness is often linked to the arts and creativity, and computational methods are linked to machinery and less intuitive ways of performing a task. I would like to challenge these misconceptions and present an argument that places computational thinking (also known as algorithmic thinking) as a type of play within itself. There is a very strong relationship between designing, playing, calculating, copying, and being creative. As I hope to show, all of these concepts are interwoven and should be at the forefront of our curricula in design and art education.

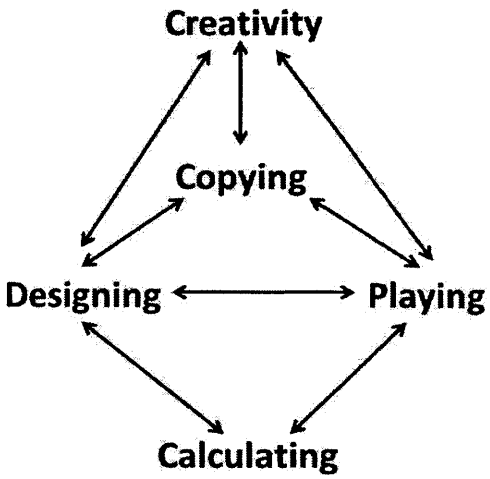

Figure 1.1: The relationship between designing, playing, calculating, copying, and creativity

Classically, architectural design encompasses three unique domains: *firmness, commodity, and delight.*[1] While firmness relates to structure and commodity relates to usability, delight relates to aesthetics. Working out the aesthetics often gives designers the greatest challenge. The design process is an elaborate play system involving each of these categories. To affirm the claim by Stiny (2006) that "*design is calculating*" (p. 14), designers must take responsibility for all of these categories of the design process. Most designers readily accept the affordances and techniques that computational tools and thinking bring to the domains of firmness and commodity. However, when we enter the domain of delight, notions of calculation and computational techniques are quickly rejected, claiming that any formal approach to design is limiting and infringes on creativity. What this

---

[1] The *Ten Books of Architecture* by Vitruvius (a 15 BC Roman architect) is where the phrase—"firmness, commodity, and delight"—originated. The book has historical significance and has served as a foundation for many great architects.

thesis aims to show is how *playful calculation* allows for there to be formal expressions of design, while promoting and fostering creative and intuitive expressions of delight.

Delight or the aesthetic component of design is at the core of playful calculation. It is important not only for architects, but for all branches of engineering. Rolfe Faste (1995) points out two distinct reasons for engineers to consider aesthetics:

1) It is vital for the creation of successful products.
2) It is a key component to being creative.

When faced with making decisions about aesthetics, designers often alter their modes of thought and methods of operation. Many in engineering separate themselves completely from aesthetic decisions by placing the responsibility of "how it looks" into the hands of a collaborator who works solely in that domain. This separation that some identify as "back-end vs. front-end" development usually results in irony; aesthetics are labeled a front-ender's design problem but are addressed at the later stages of the design process. Architects deal with aesthetics differently in that they readily embrace the aesthetic as a core component of their professional activity. However, their method of dealing with aesthetics is not done with the same clarity as other domains of design. They rely on "artistry" and "giftedness" as guiding forces to solve the problem of what looks and feels right.

Play in any educational endeavor has the ability to bring forth creativity. In fact it is impossible not to be creative while in a state of play. Singer (2011) states, *"Play and playfulness must be understood as essential elements in creativity as a whole"* (p. 87). We can safely summarize that play and creativity have a strong correlation. If we want design and art education to bridge the divide between arts and STEM (science, technology, engineering, and math), it must do so in a way that is meaningful and allows for flexible and intuitive creative processes. If we can teach our students to embrace calculation methods beyond traditional mathematics, and in turn use them to produce expressive and creative works of art, then design education curricula could become the perfect conduit to build 21st-century skills.

In Part One, I begin by discussing the foundational theories of play, design, and learning. I discuss what these ideas are individually and draw connections to show how they fit together. At the pinnacle of this discussion, I look at the work of Frederic Froebel and show how he influenced design and primary education. Froebel's gifts are of special interest, as they provide a special case study of hands-on playful learning in design. Following this section, I revisit both architecture and art education. I take a close look at the history, practices, and pedagogy of design education. To fully demonstrate this culture, I present a vignette constructed from an ethnographic observation in an architecture studio at MIT's School of Architecture and Planning. Through this I show some of the problems that occur when students do not play in their design process.

Chapter 3 takes us into the field of shape grammars. I present some of the fundamental ideas that define visual calculation through the work of Stiny and demonstrate its usefulness in design education. Furthermore, I begin to draw the connection between visual calculation and play. From this I introduce the concept of playful calculation. Chapter 4 takes visual calculation into the domain of play. I show how we can use schemas and rules to understand games and play activities. This new type of "play grammar" can be very effective for both game analysis and game creators. I take this approach to analyze a few case study examples of games and play activities.

Part Two of the thesis focusses on the research completed using an original tabletop game. The game's effectiveness as a tool for design instruction is discussed at length, as well as the insight it brings into the thinking of children as novice designers. The study was conducted at the Boston Children's Museum over a span of six months. Chapters 7 and 8 build on these studies to offer new insight on design thinking, design education, STEM education, and playful learning and creativity.

This thesis addresses a series of challenges facing education in design and STEM fields. To do so, it covers what was known previously about these problems, what I did toward solving these problems, what I think my results mean, and where and how further progress in the field can be made. This thesis makes original contributions to: 1) shape grammars; 2) play and game studies; and 3) education (design, art, and STEM subjects) as my discoveries are something hitherto unknown. The main argument simply states that "*design is both play **and** calculation; it's two sides of the same coin.*" I have arrived at these conclusions through empirical studies on the practices of design and design instruction.

Part One

Chapter 2

Play, Design, and Learning

2.1 Defining Play

While most abandon play in adult years for the “seriousness” of life, in some progressive circles play is once again emerging as a worthy endeavor. In fact, game play has become a recognized and valuable subject of research that seeks to understand certain phenomena around knowledge acquisition. Observing game play becomes a great way to understand the way people learn because it involves structured rules, flexible intuition, and meaningful decision making. Furthermore, the ways in which we learn through play present great affordances to change curricula and instruction for design studies.

Because play is an essential element to any creative endeavor (Brown, 2009; Singer, 2011), to have any meaningful reform in education (design or otherwise), play must be an essential component. To understand how play impacts both creativity and learning, we have to understand exactly what play is and how it affects the human psyche. Johan Huizinga (1950), author of the pivotal text on the history of human play, *Homo Ludens: A Study of the Play-Element in Culture,* and Roger Caillois (1961), author of *Man, Play, and Games,* offer foundational perspectives of play. Both texts give us great tools to summarize play’s usefulness in creative learning.

The book *Homo Ludens* (Greek for “man the player”) takes a historic look at the role that play has had on the human species from cave dwellers to modernity. Huizinga begins his text by criticizing how others have described play. Some deal strictly with observation, some from biological functions, and yet others as natural instinct. He points out that many leading theories about play focus on the biological aspects of play rather than the properties that truly make play special. These types of studies, he suggests, are only partial solutions to the definition of play. As he states, *“Play is irrational”* (Huizinga, 1950, p. 4).

Although play is depicted as being irrational, this should not be misunderstood as being non-serious. He further points out that play can be very serious indeed and, in fact, has been the backdrop to several wars and conflicts over time.

> *To our way of thinking, play is the direct opposite of seriousness. At first sight this opposition seems as irreducible to other categories as the play-concept itself. Examined more closely, however, the contrast between play and seriousness proves to be neither conclusive nor fixed.* (Huizinga, 1950, p. 5)

Huizinga capitalizes on the fluidity of play as being serious and non-serious by pointing to four prevalent characteristics found in play.

1) Play is a voluntary activity. It is free and, in fact, is freedom.
2) Play is not an "ordinary" or "real" sphere of activity, with a disposition all of its own.
3) Play is secluded and has limits (time and place). It begins, and then it's over. It can also be repeated.
4) Play creates order; it is order.

From these characteristics, he sums up an iconic idea of play in which he refers to the phenomena of play and play space as the *"magic circle."* In this magic circle, he describes a state of being that takes players into a mode of thinking and behaving that allows them to behave differently than they would in an active state outside play.

> *Summing up the formal characteristics of play we might call it a free activity standing quite consciously outside "ordinary" life as being "not serious", but at the same time absorbing the player intensely and utterly. It is an activity connected with no material interest, and no profit can be gained by it. It proceeds within its own proper boundaries of time and space according to fixed rules and in an orderly manner. It promotes the formation of social groupings which tend to surround themselves with secrecy and to stress their difference from the common world by disguise or other means.* (Huizinga, 1950, p. 13)

Caillois adds to Huizinga's definition of play with unique qualities of his own definition; play is: free, separate, uncertain, unproductive, governed by rules, and make-believe. Beyond these loose categories, he offers a much crisper taxonomy of play typologies. They are: *agôn, alea, mimicry,* and *ilinx* (Caillois, 1961, p. 12). *Agôn* describes all types of play that are competitive. In these scenarios, the game (or play) is set up with definitive win and lose states that emerge from playing. Although achieving the "win state" is the objective of this type of play, Huizinga would argue that staying within the magic circle is another chief objective of the player. Therefore, if a game of *agôn* becomes too easy to win, the game is in many ways unsuccessful. The player does not stay interested in play for a very long period. The balance of staying within a state a play versus achieving this win state is very similar to the description of being in a state of "flow" as described by Csikszentmihalyi (1990).

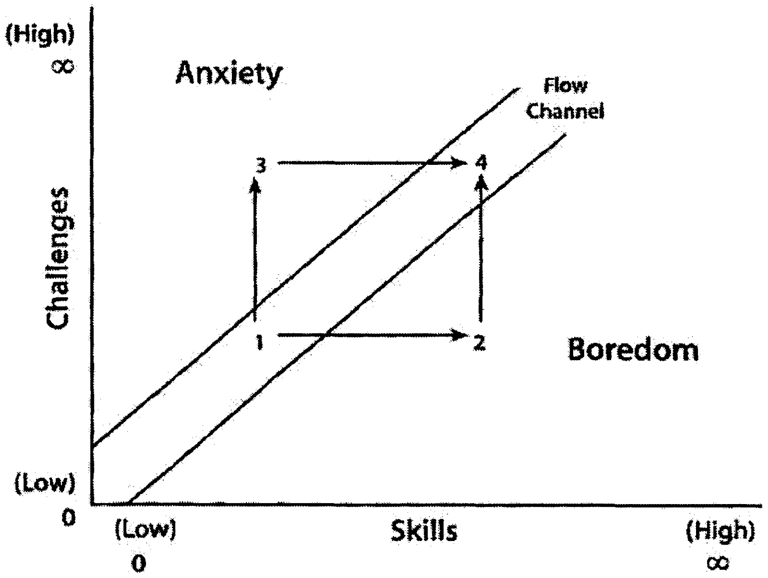

Figure 2.1: The flow diagram from Csikszentmihalyi (1990, p. 74)

Players are not only aware of their play task, but their emotional response to the play is equally a key factor. If they begin to drift into a realm of boredom or anxiety, they might abandon the play regardless of how close or far away they are to reaching the desired win state.

Caillois's second category of play is *alea. Alea,* derived from the Latin name for dice, can be described as all games of chance. This category works in great contrast to that of *agôn.* While *agôn* is achieved with great skill, work, and strategy, *alea* rejects all of these for randomness and fate. The player is completely left to the outcome emerged from the devices used to play the game. These factors could be restricted to physical components being used or might even result in factors of random luck that extend from the player's own body. For instance, rolling dice might produce their own random outcome, but games that require players to spin around with their eyes closed and point at some random location is also likely to render the same results found in other *alea* play.

Mimicry follows *alea* in Caillois's taxonomy of play. While all play does require some type of *mimicry*, this category is dedicated to play that is completely defined by imitation and pretend. Most developmental psychologists agree that this as a dominant category of play for young children (Paley, 2004; Piaget, 1960; Vygotsky, 1978). This play can be achieved with or without physical play objects. A child may play with dolls in the way that he animates these objects and gives them characteristics to play out rich narratives. In another version of *mimicry,* the child may take on a personality and become a dragon-slaying knight. If the child picks up a stick, the held object would transform into a sword, adding to the *mimicry.* This is a game that requires the transformation of meaning. The boundaries of this type of play circumscribe Huizinga's magic circle.

Caillois's final category is called *ilinx.* This category of play involves the player being placed in some type of vertigo or state of disorientation. Although this type of game often requires some physical exertion, recent technological advancements in virtual reality (VR) have been noted to produce the same effects on the player. Through VR, we can simulate with great accuracy the exhilarating rush of riding a roller coaster. On a basic level, children often spin themselves dizzy, swing swiftly on swing sets, and ride on merry-go-rounds. The players acknowledge their own individual states between balance and being out of control of their orientation. Similar to *agôn* the players must stay in the middle current of play that places them between being in an out-of-control state and being in a state fully in control of their body's orientation. Slipping too far into any of these zones would destroy the state of play and would force the player to leave the magic circle.

Caillois's taxonomy of play offers a great lens to understand the design process as a faculty of play. Many of these ideas also align with shape grammars, an algorithmic approach to design which I will discuss at length in later chapters. While play is often understated as a core activity in design, the aim of this thesis is to articulate how play exists in design, how play is computational in nature, and how we can utilize play in both practice and methods of instruction. Within the architecture design process, we can see all of the categories of Caillois's play taxonomy: *agôn, alea, mimicry,* and *ilinx.*

The *agôn* of design is at the very core of the architecture profession. In spite of the professed altruistic nature of architecture through its service to the public, ultimately architectural design is in many ways a competitive sport. Christopher Alexander (1964) touches on this in the differences between what he calls the *"unself-conscious process"* and the *"self-conscious process"* of design. In the unself-conscious process of building, all activities happen out of necessity. It is individual in the sense that builders build only for themselves and only at a time when certain life events ask for it. The means of building never change and are passed down generationally. This is not the architecture we see today, but building in a much more localized and vernacular context.

However, with the birth of the self-conscious process of building comes architecture and with it *agôn* qualities of play.

> *The development of architectural individualism is the clearest manifestation of the moment when architecture first turns into a self-conscious discipline. And the self-conscious architect's individualism is not entirely willful either. It is a natural consequence of a man's decision to devote his life exclusively to the one activity called architecture.* (Alexander, 1964, p. 57)

With the professionalization of architecture came the architect's desire to separate himself or herself from other builders. The designer's inquiry into new forms, artistic expression, and the process of acquiring commissions are all seeds of competitive play.

Harold Bloom (1973) speaks of *agôn* in his depiction of the conflict writers' face in their craft. Bloom describes a struggle poets face that I see many designers and artists facing as well in battling the internal conflict between their own ideas and the influence of their forerunners. In the design studio, students constantly work under the tutelage and pressure of professors, who at times present similar pressures on their students. When this conflict does not exist between the students' ideas and their faculty, it often exists among the students themselves. Students compete with their peers, both knowingly and unwillingly. At the highest level, design schools give prizes to the best students, and informally students take on an *agôn* mindset of play as they negotiate relationships with their colleagues.

Although *agôn* appears to happen naturally in the context of design, some would argue that its vices greatly outweigh any value it would bring to the profession or within academic environments. One such critique of competition can be found in Alfie Kohn (1986) with his controversial stance on competition, *No Contest: The Case Against Competition.* Kohn argues that competition comes at the expense of brooding hostility, developing distrust in others, and undermining productivity. He further explains through his research that collaborative learning environments are always more effective than environments based upon competition. Play has many benefits in the design process, but Kohn would argue against *agôn* in achieving design excellence.

> *What does lead to excellence then? This depends on what field and task we are talking about, but generally we find that people do terrific work when (1) they are inspired, challenged, and excited by what they are doing, and (2) they receive social support and are able to exchange ideas and collaborate effectively with others. The data shows that competition makes both less likely.* (Kohn, 1986, p. 241)

The second category of play, *alea*, comes in the design process through a variety of ways. Most skilled architects object to the component of chance and luck in the design process, but the hidden truth is that chance is indeed a key element.

Another way to understand *alea* is through games that involve extreme measures of risk. When a designer takes a risk there is a certain level of *alea* at work. Risk can come in, in many ways. While no ethical designer would take a risk at the expense of public safety (say structurally or spatially), the most noticeable forms of risk come in overall form creation. Both in art and in architecture, we find designers often taking a great risk on the public's impression of their work. In essence, they are rolling the dice with their design ideas. These can be minimal or quite large, as in the risk taken by the architect Frank Gehry. Students too are known to roll the dice with their design ideas. More cautious students might approach design by attempting to tailor every design decision to the perceived liking of their critics; others enjoy the *alea* of making design decisions that push the boundaries of acceptance.

Alea can be found in various forms of fine art, literature, film, and music—all under the guise of "aleatoricism." In truth, all art making involves chance, but these aleatoric approaches are special cases in the way the artists of this genre bring *alea* to the forefront of their endeavors. Aleatory art uses the element of chance to produce various forms of art. To do so, artists must attempt to conceal any preconceived outcomes of the process they are initiating to produce their art. In literature, writers attempting this game would try techniques in which components of their work (manuscripts or poem stanzas) would be rearranged or scrambled to yield various outcomes (Harman, 1996). Coincidently, many of the recent techniques involved in the art making of this genre take great use of computers and experimental software.

Chance and luck in the architectural design process have also come forward through the assistance of computer-coded geometric modeling.[2] The ability to create forms generated from "scripts" and codes often brings with it a certain aspect of *alea* in that the emerged forms are unknown to the designer who runs the computer program. While the designers are still in control of the process, albeit through the manipulation of computer code, the emerging output is something new each time they see it.

An example of this type of play facilitated through the use of computer coding can be seen in a project I created with the programming language *MaxScript* executed through *Autodesk's 3D Studio Max* computer modeling software. The code runs on a simple rule that takes a basic two-dimensional line shape and transforms it over a set number of frames. The following rules help explain the process.

---

[2] Mitchell, W. J., & McCullough, M. (1995). *Digital design media.* New York, NY: Van Nostrand Reinhold.

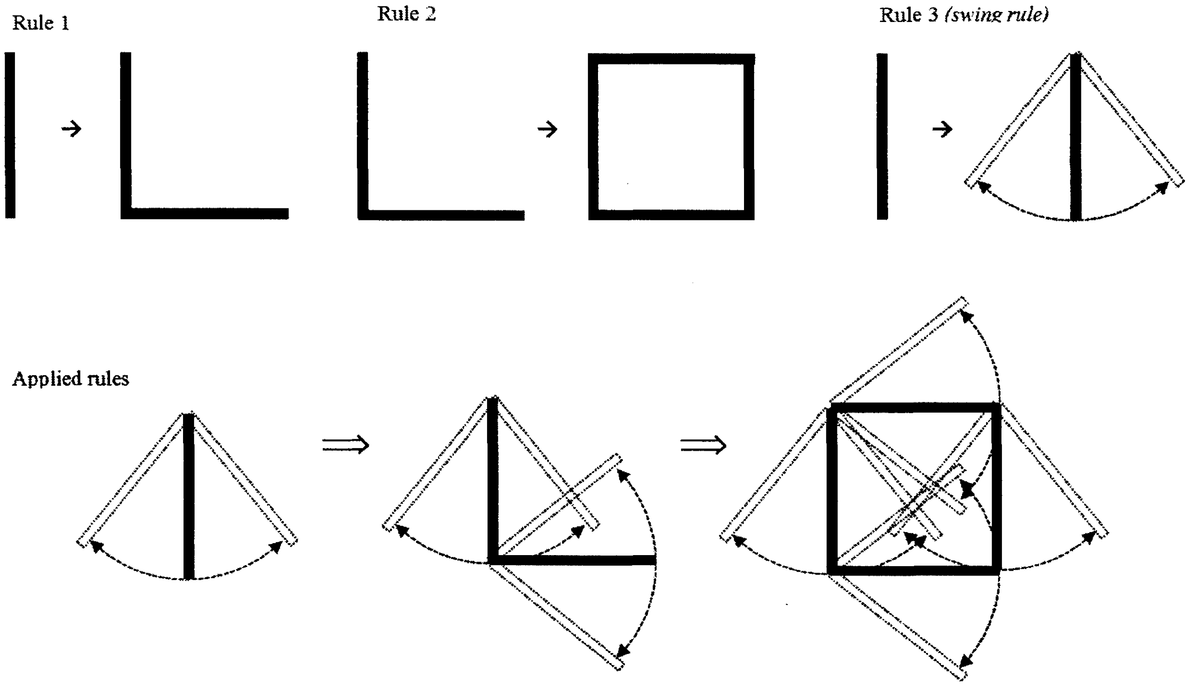

Figure 2.2: The animated swing rule

The rotation repeats in a back and forth loop that makes the line look as if it is swinging back and forth. The line is then copied to make the four sides of a square as seen in the figure above. These squares are then laid out in a grid to allow the pattern composition to take shape. Once the code is executed, the composition of animated lines begins to fold on each one and yields results that emerge from the process. For each frame of the animation, a complete new composition is discovered. As you look at the composition, your eyes lose track of the initial shape components because of the embedding. It is a playful system, akin to looking through a kaleidascope.

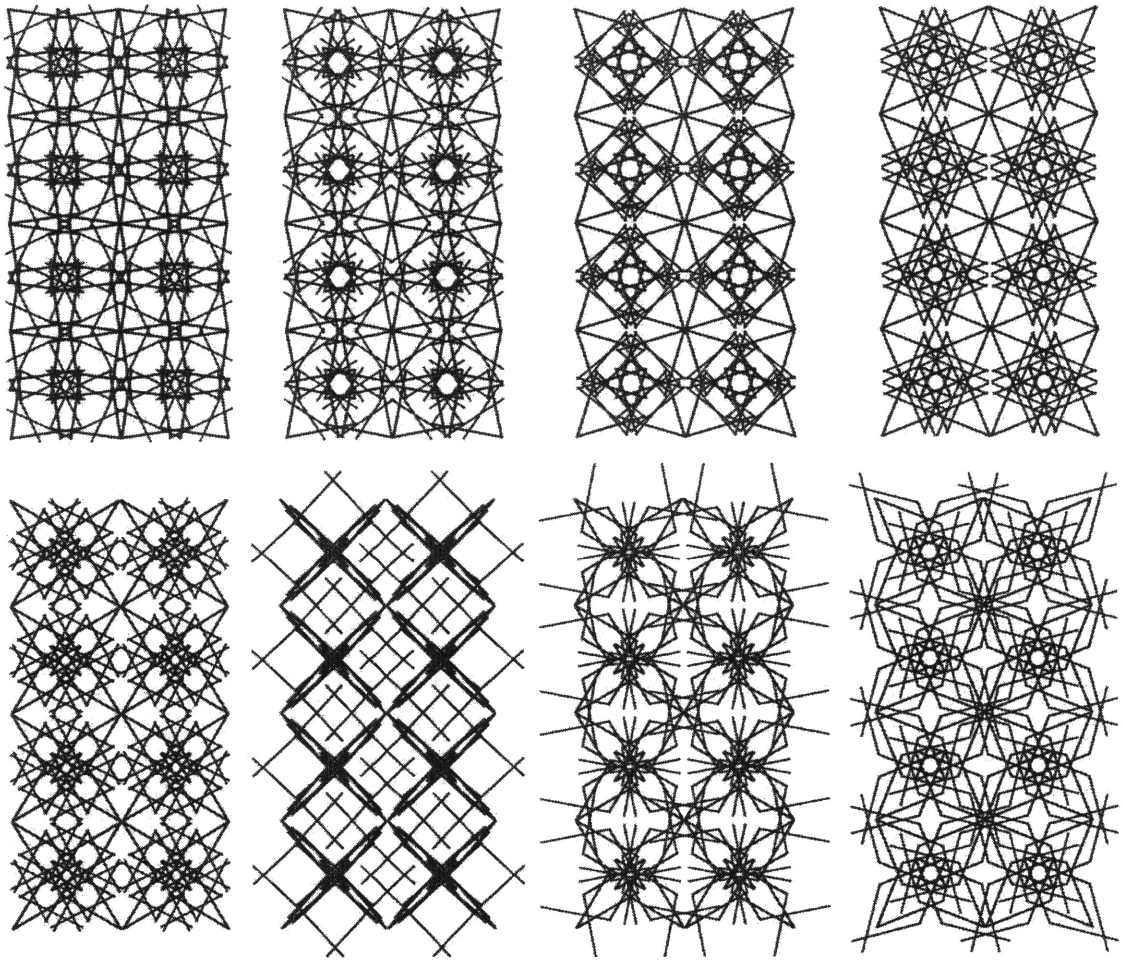

Figure 2.3: Compositions generated by the animated swing rule

In many ways, designers have created a slot machine that they can continue to play until the desired "jack pot" is seen. These types of games do not have to be computer generated. As will be demonstrated later in this thesis, traditional media such as tracing paper can yield the same results using shape grammar ideas. As designers manipulate sketched lines on transparent paper, they can continue to slide the composition around, manually generating an infinite array of designs composed by the embedded lines and emergent shapes. Playing with the serendipitous game of chance is a form of play that many designers have come to enjoy.

Mimicry, another element of play found in the design process, comes through the forms and artifacts designers use to convey their ideas. The use of a scale model, for instance, is in fact the most common form of *mimicry* found in design; it is a representation of the final design and not the design itself. This is completely different from fine art in which the player works on the final product. Architecture requires a certain amount of playful imagination for designers to make use of sketches and models to visualize inhabiting the space. Furthermore, designers are required frequently to mentally mimic the persona of the client/demographic they are designing for. If the architect is creating a fire station, for instance, and they are not (nor ever have been) fire fighters, how else can they go through the design process without this type of cognitive *mimicry?* Designers must role play in in their minds the life of the firefighter. To do so, they must first collect the data and information necessary to take on this persona, and then, as they create the various forms of representation, they enter the magic circle of make-believe and begin experiencing the design as they imagine the final user would use the space. Without *mimicry,* designing for the public falls short.

Donald Schön (1987) in *Educating the Reflective Practitioner* speaks of *mimicry* in both the design process and the way the uses of pretense and make-believe (simulacrum and simulation) occur through design instruction. The studio, as he calls it, is a "virtual world" that is *"a constructed representation of the real world of practice"* (Schön, 1987, p. 75). The graph paper, physical models, and various forms of representation are all mediums in which designers can be reflective, as if these things were the true physical artifacts. Schön emphasizes the usage of experimentation through physical materials as a means to engage in this *mimicry* play.

> *Virtual worlds are contexts for experiments within which practitioners can suspend or control some of the everyday impediments to rigorous reflection-in-action. They are representative worlds of practice in the double sense of "practice." And practice in the construction, maintenance, and use of virtual worlds develops the capacity for reflection-in-action which we call artistry.* (Schön, 1987, p. 77)

Schön also describes what sounds like *mimicry* in his depiction of the relationship between the student and the professor during desk crits (critiques). Good instructors are constantly trying to discern what the student understands, while students are trying to decipher what the instructor is trying to demonstrate, point to, or describe. The students do so by trying to apply the instructor's work to their own. One common mode of knowledge transfer between the instructor and the student in the studio is what Schön calls "demonstrating and imitating."

Instructors demonstrate, and the students imitate. This is also done by students through the usage of precedent studies in their work. Students fill themselves with design journals, magazines, and websites all as a means of this type of *mimicry* play qualities. In this play process, the imitator has to both observe and reconstruct for their own usage. The intent is that by *mimicry* the designer may see the original in a new way. This again is one of the core principles of shape grammars. Using these concepts, I will further articulate how this is both playful and computational.

Another form of *mimicry* in the design process can be seen in the actual forms created. From the very beginning of the profession, it has been said that all built forms come from nature. Columns represent trees, and ceilings represent canopies of leaves. One of the dominating perspectives throughout the years and of a few architects has been that design aesthetics are at their core imitative of nature and natural forms. Prior to the Enlightenment, several scholars argued that nature itself was the essence of beauty as it personified the creation of God.

This line of reasoning was heavily championed by the great architectural historian and art critic John Ruskin (1899).

> *I do not mean to assert that every arrangement of line is directly suggested by a natural object; but that all beautiful lines are adaptations of those which are commonest in the external creation; that in proportion to the richness of their association, the resemblance to natural work, as a type and help, must be more closely attempted, and more clearly seen; and that beyond a certain point, and that a very low one, man cannot advance in the invention of beauty, without directly imitating natural form.* (Ruskin & Sturgis, 1899, p. 111)

Goethe too aligned with this assessment, proclaiming, *"The Beautiful is a manifestation of secret laws of nature, which, without its presence, would never have been revealed"* (Goethe, Trans. Saunders, 1906, p. 171).

Hegel also explored the correlation between beauty and nature.

> *The beautiful is the Idea as the immediate unity of the Concept with its reality, the Idea, however, only in so far as this unity is present immediately in sensuous and real appearance. Now the first existence of the Idea is nature, and beauty begins as the beauty of nature.* (Hegel, Trans. Knox, 1975, p. 116)

Sometimes, this *mimicry* play is directly correlated with nature, as suggested by Ruskin. At other times, the *mimicry* may embody things without form. We can separate the two notions of *mimicry* play as being form based mimicry and translated mimicry.

1) Form Based Mimicry—the form/object is delightful due to its visual reference to other delightful objects (delightful forms that emulate other delightful forms).
2) Translated Mimicry— are forms that translate the metaphysical into the physical (delightful forms that embody things having no form—i.e., power, love, health).

For the design student, both are worthy of exploration and should be further understood to make meaningful decisions within the domain of delight.

Herzog and De Meuron's Olympic stadium, fondly called the "Birds Nest," is a classic contemporary example of this. If each built form is the embodiment of another that preceded it, then *mimicry* may be as old as the profession itself. Even if it is unclear whether or not the designer is actively engaged in *playful mimicry,* which does not diminish the public's ability to engage in this play as they rename buildings and landmarks to match what they see.

In my opinion, Caillois's final category of play, *ilinx,* offers the richest of the playful experiences found in design, and it is most closely aligned with the shape grammar principles presented in this thesis. The most common interpretations of *ilinx* is a play state that comes from being disoriented and dizzy, but we can look at the broader context of what it means to have temporaryly disrupted perception. The manipulation of perception is something that can occur from walking through abstract spaces, but this disrupted perception can also occur within the design process.

The iterative process of sketching on paper and seeing shapes embedded in each other offers great amounts of *ilinx* play. The more lines aggregate on paper, the more disrupted one's perception can become. This can easily be demonstrated by what happens with our eyes when we look at line drawings that communicate three-dimensional (3D) representation of a cube. Anyone who has taught students to draw axonometric line drawings has experienced this firsthand. Part of the difficulty in doing so is trying to keep the student from getting lost in seeing the embedded shapes in the flat two-dimensional (2D) composition on the paper. Swiss crystallographer Louis Albert Necker (1832) was first to publish the optical illusion derived from the ambiguous lines of this drawing (seen in Figure 2.5).

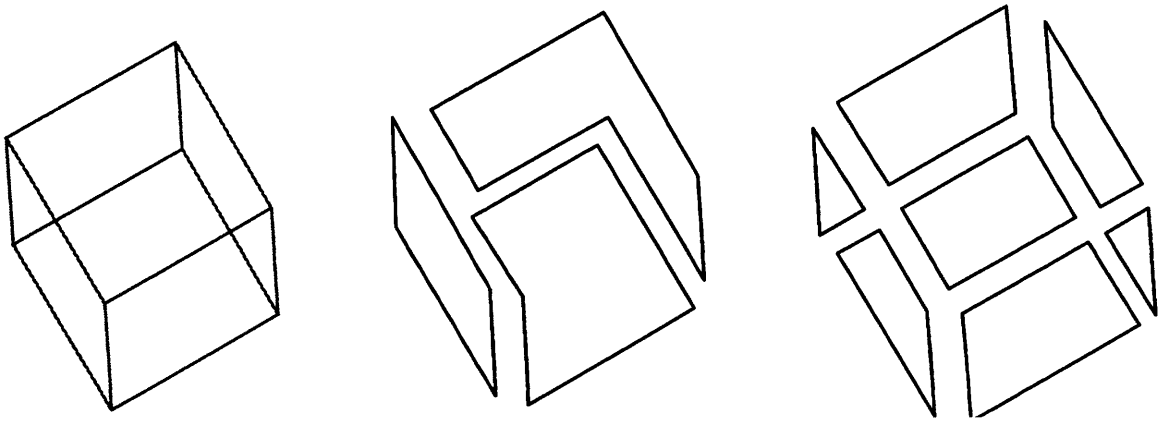

Figure 2.4: The optical illusion derived from ambiguous lines

Beyond the shapes pulled out in the figure above, there are indefinitely many other shapes embedded in the axonometric figure. This is where we find so much of the *ilinx* qualities of play in drafting these compositions. While the lines create the two-dimensional shapes, the mind is trying to interpret these shapes as a three-dimensional form. Often, the eye flips back and forth in seeing and interpreting forms from the flat 2D shapes to the 3D representational forms.

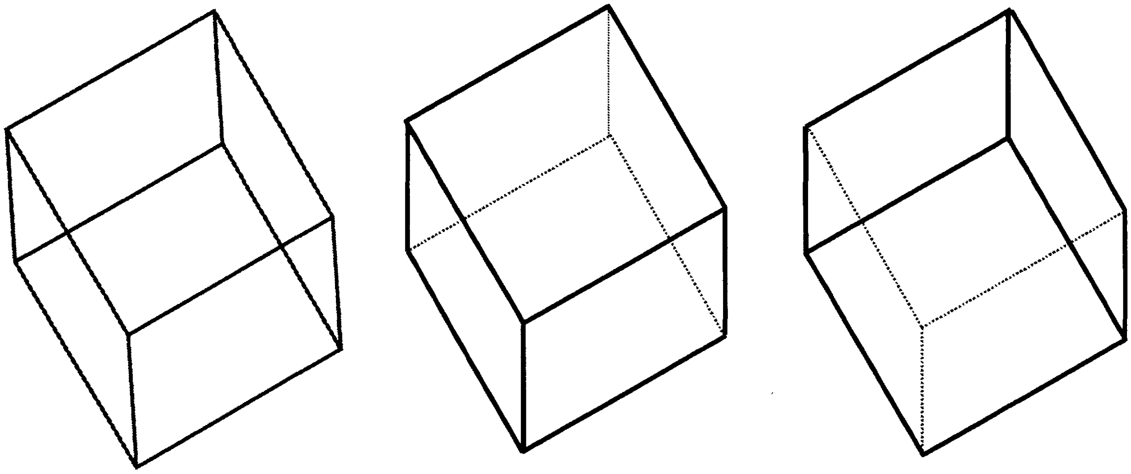

Figure 2.5: The 3D representational forms

There is much more visual disorientation beyond the flipping of dimensional interpretation. If my eyes can finally focus in to understand this drawing as a 3D form, then what is the orientation of this box? At one glance, the view appears to be looking down upon the box, and upon another glance the perspective appears that you are looking at the box from below. This type of interpretation flipping is based upon what the eye sees and is only the beginning of this visual vertigo. Once the drafter changes line weights on the composition, the disrupted perception may begin to decrease, but when lines are left as a single line weight, things are not so clear. This is what shape grammars are great for. It allows designers to use formal descriptions of this visual ambiguity while at the same time gives the designer an opportunity to play within these rules freely (see chapter 3).

Free sketching offers the same amount of *ilinx* as drafting. The visual ambiguity of sketched lines on a page increase as the designer continues this process. Only after reflection and looking at the sketch, students begin to let their mind's eye wander and fall into this playful vertigo of shapes and form. When looking at 2D compositions, the mind has to decide if it is looking at projected plan views, elevation side views, or even cross sections. Advanced artists learn to see and interpret all three (plan, elevation, and sectional views) at the same time. Designers then develop their ideas so that each perspective interacts with the other. Embedding pushes the entire process much further by allowing designers to see emergent forms throughout this process.

2.2 Defining Games

Games are a particular type of play, distinct from all other play forms. Because the line that separates "game" and "play" can sometimes be blurred, it is important to note the qualities of games that would separate it from any other play activity. Grimes and Feenberg's *Rationalizing Play* (2008) give a great diagram showing the transitional stages that take place between free play and formal games. The spectrum of play extends from free play and imagination all the way to formalized play systems that become almost "non-play" in nature.

Prior to entering a "play-mode" Grimes and Feenberg depict a period of what they call seriousness and playful tactics. What separates the playful tactics from being fully play is the lack of rules and infrequency of these actions. Playful tactics is not fully play but is the precursor to the second loop of evolution. The first transition brings the individuals into the iteration of the "play-mode" where they oscillate between being in the play state and the non-play state. Keeping in alignment with Huizinga's rule that play is not ordinary.

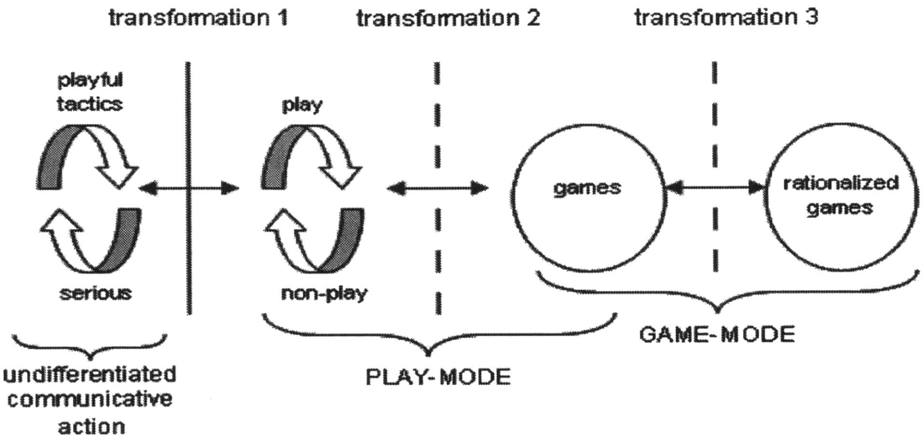

Figure 2.6: Grimes and Feenberg's game evolution diagram

Grimes and Feenberg illustrate a period that exists where an individual is slipping in and out of the magic circle. During this state, rules are also being developed and refined. Free play is often mistaken for having an absence of rules, but we see that rules exist to mediate the player from falling outside of the magic circle. If a child is in pretend play, for instance, the rules may not be explicitly stated. Yet, children are very careful to follow their own rules of make-believe to continue playing out whatever story they are creating at the time. The period of "non-play" during this stage is often dedicated to refining the game itself, whether they are adding rules, components, or players to the activity.

De Koven (2013) further sets up the divisions between different types of play in what he calls the "game community" and the "play community." In game communities, the rules and the officials constantly control the active players. They decide the suitable conditions for play to occur. However, in the play community, the players themselves are in control of the magic circle, and they constantly manipulate the boundaries to insure they are having fun.

The next transformation to "games" is very significant in the way rules are actually used. By this stage of evolution, the boundaries that define the magic circle have been clearly articulated using the set of rules. Rules might be in existence in free play as previously suggested, but only tacitly; in game play, rules are very specific and set the boundaries for the magic circle. In group play, these rules are essential to maintain order and coherency (Srowiecki, 2005; Hackman, 2002). Rule creation captures two major themes of Huizinga's qualifiers for play to happen. Through the creation of rules, we have the limitation of time and place and the creation of order. Rules are also a major component that illuminates the calculation qualities of play, making it computational and creative.

The final stage of what they call rationalized games is a condition in which the player is still engaged in the game but no longer in a state of play. This phenomenon is most common among professional athletes who profess that the sport they play is no longer "fun." Some designers pass through this same phase, when the play component of the game has been replaced with the rational overthinking of the process. Suddenly, the individual has moved outside of the magic circle back into the domain of everyday (adult) seriousness.

The evolutionary stages of play to games described by Grimes and Feenberg are useful in looking at the entire enterprise of play activities, but other researchers are not so quick to draw clean distinctions between play and games. Salen and Zimmerman (2004) summarize three levels: being playful, ludic activities, and game play. In each of these, the separating factor from free play to games still has to do with the treatment of rules.

Salen and Zimmerman further present an interesting paradox in that "games" are a subcategory of play, but play can also be a subcomponent of games. There are many components of games of which play is just one element, but in every form of play there is some game or rule element at work (Huizinga, 1950; Vygotsky, 1978).

> *All play has its rules. They determine what "holds" in the temporary world circumscribed by play. The rules of a game are absolutely binding and allow no doubt.* (Huizinga, 1950, p. 11)

To say all play contains an element of games and all games contain the element of play may sound contradictory, but the same juxtaposition exists with play and design. In all aspects of design there exist some elements of play, and in all play there is a design component.[3] This

---

[3] The original play diagram was created by Salen & Zimmerman (2004). In it, they place play and game in the Venn diagram to discuss the relationships between both.

relationship works a lot like shape grammars. There is no either-or; you can see the relationship as both-and. Play and design are embedded within each other.

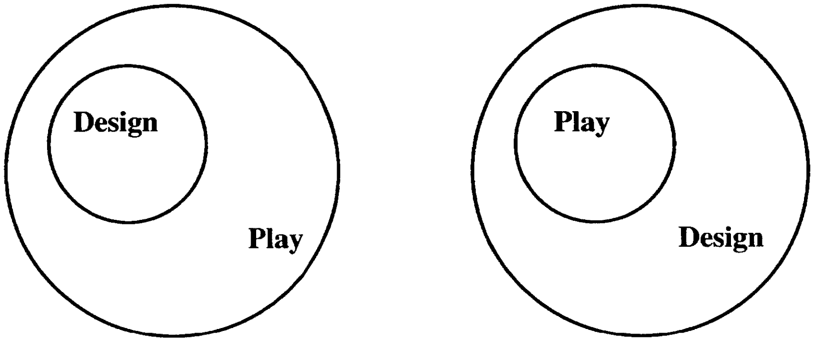

Figure 2.7: The juxtaposition of design and play

2.3 Types of Learning and Underlying Models of Mind

Discussing the various models of learning is valuable to discussing the affordances of play. Because these models are constantly being tweaked (and in some cases replaced), we may never have a fixed definition of learning. New models emerge over time, replacing previously held notions of how people learn. Yet many in the learning sciences are still on the quest to firmly define best practices for learning.

2.3.1 Behaviorism

The *Behaviorist* model of learning might be one of the oldest but is still actively used. This learning model insists the learner is someone that can be programmed, almost as one would program a machine. Often carried out by routine drills, and repetition as a means to install information, this model reduces learning to drill and practice, and a response to stimuli, through external reinforcement. B.F. Skinner and Ivan Pavlov are the most noted advocates of

---

this approach to learning. Both researchers built their research primarily on the cause and effect of human and animal responses to certain stimuli and work conditions.

2.3.2 Inneism

Inneism introduces biological determinism as an understanding for learning development. In this model of learning, certain things an individual learns from birth are independent from that individual's learning environment. These claims are very hard to prove, and some of the core arguments have been discredited by the science community. However, many of these notions align with different religious beliefs.

2.3.3 Cognitivism

The *Cognovits* model of learning suggests a more computational model of learning. In it, the mind is likened to a machine that can be programmed and, in turn, operates as an information processor. Knowledge is seen as information to be transmitted at one end and encoded at the other, stored in memory, retrieved, and re-applied. This view of learning was made popular in the 1960s at the same time major advances were occurring in computer science. Lindsay and Norman (1972) capitalized on these ideas with their book, *Human Information Processing: An Introduction to Psychology,* through which they depict human cognition as being similar to that of computers.

2.3.4 Constructivism

The *Constructivist* learning model, as the name suggests, states that learning happens as individuals construct their own learning experiences. Vygotsky and Piaget both recognized the significance the child's environment had on his/her learning and development. They believed there is no better way for children to construct meaningful experiences than through play. Piaget believed that it was, in great part, through play—and suspension of disbelief—that children start to establish a dialog between what is and what could be, between possibilities and actualities (which Piaget saw as the crux of what it means to be intelligent in the first place).[4] For Piaget, teaching could never be direct, and knowledge was not deliverable information as the *Cognovits* suggest (Ackermann, 2004).

2.4 Types of Education Theories and Practices

Several theories on education have risen from the adoption of specific learning theories. Educational approaches are built on theories of the mind; each epistemological foundation comes with its own consequences: From *Behaviorism,* we get *Instructionism,* and from *Constructivism,* we find *Constructionism.* The relationship between educational theory and learning theory are inseparable.

2.4.1 Instructionism

The *Instructionism* model of education suggests that individuals learn through a direct flow of information between the learner and the instrument of instruction. This model of education is built on the foundation of behaviorism and cognitivist models of development. If the human brain is a computer to be programmed, the instructor takes on the role of the programmer. While the instrument of instruction is usually a teacher (instructor), this can also be supplemented with books, recorded lectures, and (in today's time) apps and computer programs. This learning model places great emphasis on the role of the instructor (or instruction material) as a core value to the success of learning.[5]

2.4.2 Constructionism

Constructionism is an educational model coined by Seymour Papert. Papert built heavily on the constructivist learning model (which explains the likeness of the names). The theory purports that individuals learn by constructing their own learning experiences (as *Constructivism* suggests), but this is most effectively done through making and building. Contrary to the *Instructionism* model, emphasis is not placed on the instructor or various

---

[4] Eysenck, M. W. (1993). *Principles of cognitive psychology.* Hove, UK: L. Erlbaum Associates.

[5] Directed Instruction or Objectivism is grounded primarily in behaviorist learning theory and the information-processing branch of the cognitive learning theories. In this model, learning is transmitted knowledge. Teaching should be directed, systematic, and structured.

instruments of information. More focus is placed on the learners and the things that matter most to them. Most art-education curricula widely accept this approach as the arts rest on self-expression and individual exploration.[6] Papert's work was influential in establishing early initiatives in teaching computer programming to children and paved the way for the "Maker Movement" and various other design-based learning models.[7]

One critical disposition between these two previously mentioned learning models is their unique treatment of experts and novices. *Constructionism* tends to empower the novice, giving no preferable treatment to the expert. In fact, if experts have taken on instructor roles, their job is to use restraint in the display of their expert knowledge in order to allow students to build their own experiences through trial and error (Dewey, 1938). In this way, the expert is leading by scaffolding the activities for the novice to learn. *Instructionism* works almost in exact reversal. In this educational model, it is expected that the experts pour knowledge into the heads of the novices. The novices are at the mercy of the experts; without this relationship, the novices cannot learn. This education approach can prove to be very dangerous, as it rests heavily on the personalities and relationships of the experts/instructors. Ironically, this is also the model of education found most often in art and design school programs through the master-student relationship.

2.4.3 Mindfulness

Mindfulness is a learning approach set by Ellen Langer (1989). In this approach, she sets forth a model that has three major characteristics. Mindful learning is one that continues to create

---

[6] Constructivist or inquiry-based learning evolved from other branches of cognitive learning theory. Constructivists believe humans build their knowledge in their minds by participating in the experiences they have. Learning in this model occurs when individuals construct both a framework for learning and their own unique version of the knowledge, molded by background, experiences, and environment.

[7] Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas.* Further discussions can be found in Ackermann, E. (1996). Perspective-taking and object construction: Two keys to learning, and in *Constructionism in practice: Designing, thinking, and learning in a digital world* (Y. Kafai & M. Resnick, Eds.). Mahwah, NJ: Lawrence Erlbaum, Publishers, pp. 25-37.

new categories, it is open to new information, and it has an implicit awareness of multiple perspectives. At the core of mindfulness, Langer champions play as a means to keep fresh ideas and not get entrapped by a singular perspective of the world. She says, *"Ironically, although work may often be accomplished mindlessly, with a sense of certainty, play is almost always mindful"* (Langer, 1989, p. 144).

2.4.4 Ludenism

"*Ludenism*," as I would like to propose, may be the best new learning philosophy for general and design education. The effect play (being in the ludic state) has on learning is highly documented but has not been given its proper place among the great theoretical philosophies in the learning sciences. Components of a *Ludenist* model of learning do show up in constructionism, incidental learning, and design-based learning models. The explicit emphasis of a play at the core of this model makes it unique.

A learning experience that is playful is a more meaningful learning experience than that acquired by information dictated from a teacher. Traditional elementary and Pre-K art education has led the way supporting the play pedagogy (Eisner, 2002; Hetland, Winner, Veenema, & Sheridan, 2007), but often curricula for STEM subjects (science, technology, engineering, and math) are void of the play element. As art educators look to adopt new technologies in art education curricula, they should pay special attention not to lose the pedagogy of playfulness that has led the way for innovation and creativity in the arts. The educator is responsible to set up a playful learning environment.

Games have great impact for learning in groups. Richard Hackman (2002) points out three factors that are critical for healthy group dynamics: The task is meaningful to its members, there is collective responsibility, and there is knowledge of results. Play, and especially game play, has a great way of soliciting significance and meaning to players through a system of internal and external rewards. The placement of "win states" brings a collective group of players together to establish collective responsibility to reach the set of learning objectives (Gee, 2007). Furthermore, group learning is carried out through play in how it solicits multiplies perspectives from the players. Langer (1996) states,

> *We can introduce material through games, because in games players vary their responses to fool their opponents or to look more closely at all aspects of the situation to figure out how to win* (p. 42).

Because good learning practices require divergent thinking and the development of multiple perspectives on the individual level (Dewey, 1934; Perkins, 1942; Langer, 1997; Eisner, 2002), this may be amplified when playing/learning occurs with a diverse group of individuals.

Games have also been used to promote learning to design. Lawson's (1990) *How Designers Think* highlighted several game examples from the 70s used in the studio. These games mostly focused on simulating, through role play, real world client-public-designer relationships or developing group behavior and norms within the design studio. These games clearly fall under Caillois's *mimicry* classification of play, but they also allow for some of the risk behavior one would find in *alea* qualities of play. Much of the same qualities of these physical board games exist in computer role playing games such as *Sim City* by EA Games and *Urban Tycoon* by Touch Soft Mobile. Even though these games are greatly limited in their mechanics, they do allow the player to engage in design actions and decisions that mimic real world scenarios.

Game play examples that align more with the design thinking and the iterative nature of the design process are harder to come by. A great example of this quality of game can be found in the work of Bill Porter in the *Silent Game* and Habraken's (1987) *Concept Design Games*. Porter's work deals with how we use our eyes to see design and establish meaning both as an individual and collectively.[8] This seeing and embedding meaning then informs action, all of which is done in silent as the name suggests. Habraken's *Concept Design Games* were not developed for students to use as a tool for design; rather, by playing these games, they were to

---

[8] Bill Porter is an emeritus Professor at MIT's School of Architecture and Planning. He developed the *Silent Games* alongside professor Terry Knight (of Design and Computation) as a way to reveal the tacit knowledge developed between designers in a collaborative design task. Players develop rules to mediate the decisions they make. The game assigns roles: two builders (Builder A and Builder B) and one observer. The game is played in silence as the name suggests. Builder A builds for 12 minutes, followed by Builder B that begins to build demonstrating an understanding of the gestures offered by Builder A (8 minutes). Builder A then follows with building to confirm or clarify Builder B's understanding. The observer then explains what happened, which then generates a larger discussion among all parties.

offer new insight on what it means to design. In essence, they were research tools for educators. Some of the findings from these games reflect the collaborative nature of design as well as the temporal nature of architectural practice.[9]

2.5 Developmental Stages in Play and Learning

The early supporters of play in childhood only took into consideration the value mental and physical leisure had on child development. This would change as researchers looked at the advantages play had for a child to develop and learn. As new theories emerged on individual learning, play once again found itself at the center of attention. One of the first theories to disrupt traditional methods of education was John Dewey's (1938) ideas on *"learning by experience."* Dewey believed that the best way children could learn was for them to have a meaningful experience and through that experience develop a deep understanding of the material. This theory of education was at the foundation of progressive education in the United States (US), and much in line with Piaget's *Constructivism* and Papert's *Constructivism.* Children construct their knowledge through meaningful—and firsthand—experiences. They were to be scaffolded and supported by caring and knowledgeable adults (teachers, parents) who acted more as "guides on the side" than "sages on a stage."

Piaget's work showed how children passed through very distinct stages of development; through many stages, play that allowed children to embrace change (Thomas & Brown, 2011; Singer, 1978). For both Piaget and Vygotsky, play was about the child creating imaginary situations (pretense and fantasy play). Vygotsky further noted that especially young children wrestle with perception of object (color and shape) and perception of meaning. For children "object" dominates the object-over-meaning relationship, but during play the formula is inverted to meaning-over-object (Vygotsky, 1978). Children at play are constantly honing their "seeing" skills. The ability to look at something and transform its meaning is foundational to creative thinking.

---

[9] Habraken's *Concept Design Games* were a series of studies carried out as games at MIT's Department of Architecture with Mark D. Gross, James Anderson, Nabeel Hamdi, John Dale, Sergio Palleroni, Ellen Saslaw, and Ming-Hung Wang.

The ability to see things in new ways during play is also an effect of Huizinga's moving in and out of the magic circle. The magic circle offers a distinct break from the "reality" in which the player lives. In group play, the magic circle expands to a shared acceptance of the reality within the game. Each player is invested in keeping the circle intact all for the sake of having "fun." The magic circle is temporal and allows players to abide by a different set of rules, resulting in behaviors and actions that are permissible to that time and place. Vygotsky (1978) points out that children can often carry out more complex tasks during play than they would outside of play. This is often achieved when children are playing a game of imitation. During this play activity, they are embodying some persona outside their own. For learning to occur, however, students must learn to transport the experiences from the magic circle into other domains. Gee (2007) asserts,

> *The learner needs to learn not only how to understand and produce meanings in a particular semiotic domain but, in addition, needs to learn how to think about the domain at a "meta" level as a complex system of interrelated parts* (p. 23).

Gee extends the inquiry of play and learning from K-12 to adult education. Play contains a four-step process of probing, hypothesizing, re-probing, and then rejecting or accepting the hypothesis (Gee, 2007). Although this depiction of play should not be taken literally as a step-by-step formula, it does capture many learning principles of play that can be classified as "mindful." Mindfulness, as stated by Langer (1997), is a key element of effective learning and is almost always present in play. Langer further refers to play and mindfulness as "sideways learning." Sideways learning has five unique qualities: openness to novelty, alertness to distinction, sensitivity to different contexts, implicit—if not explicit—awareness of multiple perspectives, and oriented in the present (Langer, 1997). In all of these qualities, the play element is in action.

Playful learning experiences are more meaningful than any amount of information that could be dictated from a teacher. As a result of this adopted pedagogy the chief role of the educator is to set up the learning environment, an environment of play. Thomas and Brown (2011) state that *"when play happens within a medium for learning—much like a culture in a petri dish—it creates a context in which information, ideas, and passions grow"* (p. 18).The writings of Piaget, Dewey, Vygotsky, and Montessori all insist that children do not learn through teachers but through playful experiences.

2.6 Friedrich Froebel

Friedrich Froebel was a 19th-century German educator and philosopher who developed a unique system for teaching children. His work helped define the leading primary-education (K-5) curricula we see today. Froebel was heavily influenced by Johann Pestalozzi, a Swiss educator who was impactful on education in his own right.[10] Froebel's influence on education, however, has proven to be more lasting and broadly known due to his major literary works. He is also credited for coining the word "kindergarten," a name he invented for the Institute of Play and Learning he founded in 1837. Froebel was very religious and built many of his education ideas from his religious convictions.

Early in his career, Froebel developed a deep love for geometry. His interest for formal mathematics blossomed when this inquiry spilled over into insight on how geometry and order revealed itself in nature. For Froebel, this was a manifestation of the "Divine Being." As his interest expanded, he had critical work experiences that helped him transition these interests into ideas about educational reform. His experiences were very broad, as an apprentice woodsman and land surveyor, and as a student of botany, mineralogy, and architecture.

By the time Froebel met Pestalozzi, he had chosen a career in education by accepting a teaching position at the Frankfurt Model School. It was at this time that Froebel had discovered the writings of Jean Jacques Rousseau. Rousseau's literary work *Emile* was so radical on education and society at the time that it was banned in Paris and Geneva and was publicly burned right before the French Revolution.[11] Froebel's attraction to the work was mostly due to the emphasis Rousseau placed on the new imagined childhood. Prior to Froebel's work, children under the age of seven were not schooled. Froebel read the work of Rousseau while reflecting on his own childhood, one that was spent in nature and full of wonder (Brosterman, 1997; Froebel, 1887).

---

[10] Barnard, H., & Pestalozzi, J. (1859). *Pestalozzi and Pestalozzianism: Life, educational principles, and methods of Johann Heinrich Pestalozzi.* F.C. Brownell.

[11] Rousseau, J., & Foxley, B. (1974). *Emile.* London, England: Dent. Stiny, G. (2010).

2.6.1 Froebel's Educational Theories

At the core of Froebel's educational philosophy was the component of play. This was no ordinary play, but was carefully scripted by the instructor. The scripting of play was very intentional and was meant to bring the children to a deeper understanding of themselves, God, and nature. Some of the activities of play included singing, dancing, storytelling, gardening, and the most famous of all, his *Gifts* and *Occupations* (Wiggin & Smith, 1895).

Pestalozzi had a famous saying, "Learning by head, hand, and heart." Likewise, for Froebel, the goal of education extended far beyond the students' ability to learn facts or develop skills. Froebel had a holistic view of education that included his Christian beliefs which had shaped his perspective of humanity. He said,

> *Man ought not to be contented with teaching merely directed to satisfy his needs as a child of earth, but must demand and receive from education a true foundation, a creative, satisfying preparation for all the grades of development of nature and the world which mankind encounters, and for the everlasting here and beyond of each new moment of existence, for the everlasting rest, the everlasting activity, the everlasting life in God. As, however, it is only as a Christian, be he consciously or unconsciously so, baptized or unbaptized, taking the Christian name or rejecting it, that he can think and act after this fashion, you can see at once the reason why my system of education feels itself to be, and in fact claims to be, an education after the true spirit, and following the precepts of Jesus Christ.* (Chapman, 1984, p. 125*)*

Brosterman's *Reinventing Kindergarten* (1997) gives very little credence to Froebel's religious positions. In fact, Brosterman makes large claims that try to recast Froebel as a pantheist. My understanding of Froebel's religious beliefs places him in what we call today "conservative Christianity." I also believe a closer look at Froebel's Christianity provides a rich understanding on his brand of education that is both playful and creative.

For Froebel, religion meant living a life that was not defined by the conventional boundaries of modern science. By this time, religious perspectives had received a reputation in the scientific community for being closed-minded and having a narrow view of the world, but for Froebel religion served an opposite purpose. Froebel's beliefs allowed him to transcend conventional knowledge to reference a domain of existence that extended beyond the physical world. As Einstein said, *"Science without religion is lame, religion without science is* *blind."*[12] Furthermore, Froebel's perspective of "oneness" with the universe is akin to what several spiritualists speak of today. Some of the literature today that speaks of *mindfulness* or being in "*flow*" all extend to a more explicit religious pedagogy found in Froebel's writings. And indeed, Froebel creates ways to explore these relationships and writes them out with such detail they can be understood as formula expressions. As he said,

> ***Play** is the purist, the most spiritual, activity of man at this stage, and, at the same time, typical of human life as a whole – of the inner hidden natural life in man and all things. It gives, therefore, joy, freedom, contentment, inner and outer rest, peace with the world. It holds the sources of all that is good.* (Froebel, Trans. Hailmann, 1826, p. 55)
>
> *Man + Play = Joy, Freedom, Contentment, Rest, Peace*

2.6.2 Froebel's Gifts

Froebel was not only an educator, but was a designer of objects that lead to impactful educational experiences. Some of the noted individuals who testified to the impact of playing with Froebel's gifts as children were Frank Lloyd Wright, Charles Eames, Buckminster Fuller, Johannes Itten, Paul Klee, and even Albert Einstein. Each had their own childhood story of playing with Froebel's gifts.

Froebel's gifts are a set of playful manipulatives that allowed children to explore, discover, and create. There has been some dispute on exactly how many gifts Froebel originally created. In truth, Froebel's intent was for the gift set to continually be expanded upon, for they represented a set of prototypical play materials that could evolve. Milton Bradley was one of the first companies to capitalize on this as they successfully turned the gifts into a commercial toy product. In the early years, the gifts were well crafted out of wood and shipped in small elegant wooden boxes with the gifts' label on the exterior (Brosterman, 1997).

---

[12] This excerpt stems from: Einstein, A. (1941). Science, philosophy and religion, a symposium. Paper presented at Science, Philosophy and Religion, A Symposium: Conference on Science, Philosophy and Religion in Their Relation to the Democratic Way of Life, Inc., New York.

Gifts 3to 7 are the most popular and widely known of Froebel's system. Together they comprise explorations of form and space on both a 2D plane and in 3D space. Gifts 3, 4, 5, and 6 were all comprised of solid wooden block pieces. Each of these had a kit of wooden components that once combined together could make a perfect cube. Gift 7 was a set of flat tiles presented either in wood or in colored paper (the paper version was referred to as *parquetry*). This play differed from the previous gifts in that the play was restricted to the surface of the table or floor to created compositions two-dimensionally (Brosterman, 1997; Wiggin and Smith, 1895).

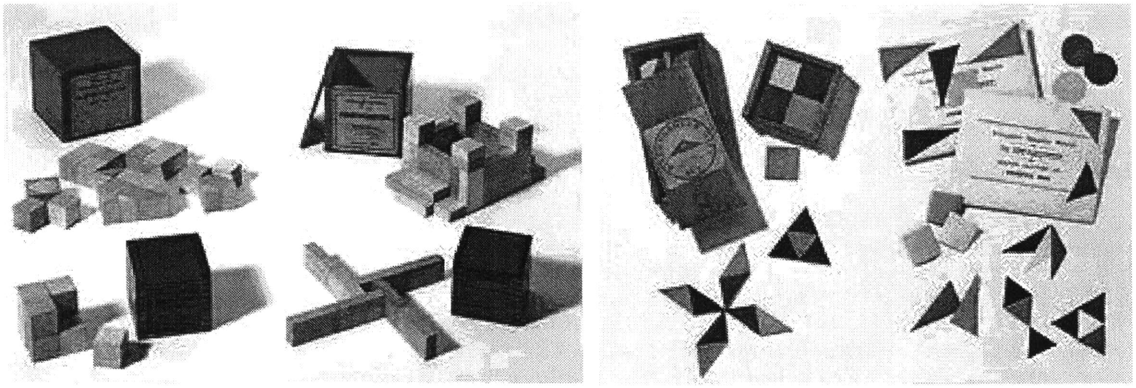

Figure 2.8: Froebel's gifts (Brosterman, 1997, pp. 52-53 and 60-61)

Traditional art and design curricula begin with 2D compositions and later move into the third. It is interesting to note that, in Froebel's system, the 2D composition is of a higher order of abstraction than that of the three dimensions. In Froebel's system, children begin with 3D gifts and work their way up to play with 2D pieces. Froebel realized the flatness and two-dimensionality of these pieces brought forth an ambiguity and abstractness that the child would have to wrestle with.

Although the gift sets did not come with formal instructions (as you see today) communicating how to construct various forms, Froebel did write about the types of compositions children could create in three distinct categories: *forms of life, forms of knowledge,* and *forms of beauty* (Brosterman, 1997; Stiny, 1980; Wiggin and Smith, 1895). *Forms of life* represented the objects children interacted with in their everyday experiences. Usually these types of forms would be domestic items or structures that were visually recognizable to the child's region.

Forms of knowledge were compositions that expressed the principles of mathematics and geometry. Through this type of playful composition, the child would understand proportions, spatial relationships, and basic addition and subtraction principles. Finally, there were the *forms of beauty* which expressed an intersection between nature and geometry. Froebel's love for this subject was no clearer in this activity, as it promoted children to explore the natural universe through the expression of geometric compositions. Froebel was moving STEM to STEAM (science, technology, engineering, art, and math) long before the creation of these overused acronyms.

2.6.3 Froebel's Influence on the Design Education

The gifts themselves had a great influence on individual designers and design education at large. Frank Lloyd Wright might have been the most famous and vocal individual to speak of the Froebel gifts as he spoke fondly of his childhood experiences playing with them.[13] Truly the body of his built work correlates directly with the connection between nature and geometry. The Froebel gifts also are the precursor to several design exercises students perform during the first few years of architecture study. The study of space and form through simple primitives is a curriculum standard in most schools, and it all points back to the Bauhaus design education approach which was impacted by the work of Froebel.

Froebel also had a profound influence on the educational philosophies of Walter Gropius and other founders of the Bauhaus. The gifts were very instrumental in the formation of their design curriculum. Much of Gropius's appreciation of the kindergarten system is due to his own childhood education in Germany, which was still operating under the system created by Friedrich Froebel some forty years before his birth. Gropius was born in 1883 in Berlin, Germany, at a time when Froebel's philosophies had been well established as a foundation for primary education.

Walter Gropius points out several critical moments in the educational path of an aspiring professional designer in his diagram of the *"training of an architect."* At the beginning he notes, *"Nurseries/Kindergarten—a place that stimulates the urge to play"* (Ockman, et al.,

---

[13] Wright, F. L. (1957). *A testament.* New York: Horizon.

2012, p. 21). Gropius understood that play pedagogy was important for the foundational years of study but seemed to drop the ball in moving it forward. He further states that public schools, private schools, and high schools were to be the places that children develop, *"manual skill and form perception."* He further describes it as a *"transition from play to work"* (Ockman, et al., 2012, p. 21). This would seem odd as the Bauhaus is thought of as being a very playful learning environment. From a Froebelian pedagogy, play is necessary to give learners a deeper appreciation of their craft. What I will show in the chapters to come is how this type of play can get students to calculate in new modalities.

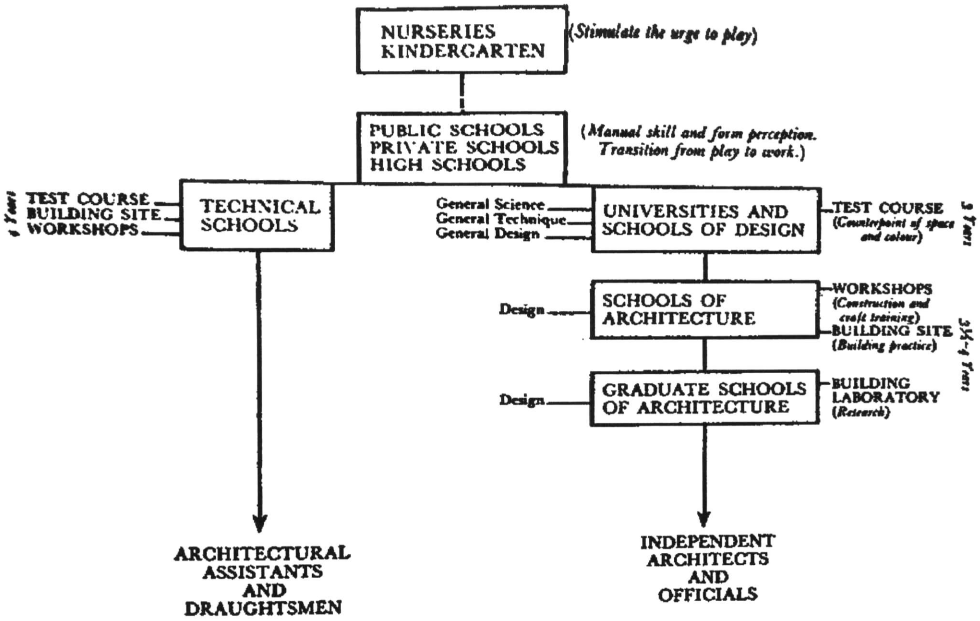

Figure 2.9: Gropius education diagram (Ockman, et al., 2012, p. 21)

The significance of play, as a means for fostering creativity, has been long lost in many contemporary design school programs. One might say that play has reached the domain of "rationalized games," as depicted in Grimes and Feenberg's diagram. The play element in the upper years of design study still exists as expressed earlier. If we look, we still find Caillois's *agôn, alea, mimicry,* and *ilinx.* But by not having placed emphasis on this (from a curriculum standard), these are lost to both students and instructors. This thesis looks at how we can bring these to the forefront of our design activities and curricula through formal calculation.

2.7 Design Instruction

Design students and educators know that their craft is best learned in action, through the experience of the designing. This can also be labeled *"situated learning"* (Eisner, 2002). That is to say, design is not learned by reading a book or watching secondhand where someone designs, but it is learned by designers actively doing the same thing they are trying to learn. This does not rule out the before mentioned techniques as methods used to understand design. It disrupts the hierarchy of learning activities as to insure that these activities are not the primary experience. As a result, the design studio is at the core of design students' education. From the first semester of architecture school, students are thrust into studio design projects where they begin to craft their knowledge on the subject. [14]

Most design schools have in their program a "basic design" or "beginning design" curriculum aimed to transition first-year students into design. This curriculum is usually made up of courses and seminars that present both the foundational skills and pedagogy of design to the students. The basic design curriculum can be seen from two opposing perspectives. The overtly abstract nature of projects without function or practical use could be negatively seen as what some call the "export paradigm." David Perkins, in his foreword to the book *Studio Thinking* (Hetland, 2007), points out that students are often forced to learn things only applied and used for some hypothetical future. On the other hand, the basic design curriculum can be seen as a way of "scaffolding" information. Lev Vygotsky's (1934) theory on the *zone of proximal development* has been re-appropriated from childhood development to give educators an example on the importance of curriculum design. Instructors should tailor

---

[14] Historically the design experience was not given to students at the beginning of their academic experience. The German Polytechnic model of design education from which the early American architecture programs were modeled on (including MIT in 1866) placed heavy emphasis on studying math, physics, and technical drawing in the early years with a full year of design not coming until the fifth year of study (Ockman, 2012). The Beaux-Arts traditions of design education was first to introduce design projects at the very first year of study. This was not fully adopted by American institutions until the early 1900s. The 1930s brought the Bauhaus as the last great influence on American architectural education. The Bauhaus kept the Beaux-Arts traditions of studio-based projects but with it introduced the concept of "Basic Design" as the focus of study for the student's first years.

projects that reflect on both what the students know and where they need to get to by the end of a semester. In many ways, the basic design studio with all of its abstraction is helping bridge the gap from design novice to design student.

The studio's project-based curriculum for upper year design students falls very much in line with the educational philosophies of Dewey (Eisner, 2004; Fisher, 2000; Ockman, 2012). Around the same time Gropius was establishing his Bauhaus system in architecture schools, Dewey was making his own progressive reforms to K-12 education. The two philosophies would align nicely in several ways. Dewey (1929) made the case that young learners should be engaged in meaningful experiences and explore their environment hands-on. The studio approach, as created by the Bauhaus and still in use today, exemplifies these hands-on explorations. In some cases, students engage directly with material and full-scale explorations of built form; in other instances, the exploration takes places graphically through the sketch, where students have *"reflective conversations"* with their drawings to explore ideas of form and space (Schön, 1982; Lawson, 2004). Although architecture and design by nature are concrete fields of study (as opposed to mathematics and philosophy), there is still a strong historical connection to Froebel's influence to promote learning through the playful manipulation of objects.

2.8 Art Instruction: The Exploration of Aesthetics

The arts have had a stronger connection with play over the years than that of design education. The performing arts even use the word "play" to describe its practices. Musicians "play" their instruments; in theater, one "plays a character." Perhaps, it is time for designers to say they "play" the pen, or they "play" the paper. It would be fitting to do this, and visual calculation's usage of shapes and rules could lead the way to play this game. When it comes to aesthetics, the creative process must be an act of play.

The factor separating art education most from design education is the focus on aesthetics. Although art educators deal with the subject matter of "beauty" in art, very few present a practical framework for which to have an assessment guide for the level of beauty in a given piece of art. Furthermore, teaching individuals to make objects that are aesthetically pleasing is obscure. Some say it cannot be done. Few have provided a general framework to teach the creation of beauty. Added ambiguity on the subject has forced polar views on the subject of "beauty" or "delight." Some try to use colorful narratives and metaphor to explain its existence; others avoid it all together, claiming it to be a byproduct of the functional and social components of design. Walter Gropius, notably coined the formula: Firmness + Commodity = Delight.[15] The varying perspectives on beauty have led to the frustration of students and instructors alike, both in the professional studio and in classroom settings. As students of design and architecture struggle with beauty's definition and methods of production, instructors look for means of assessment beyond subjective positioning.

Psychologists, philosophers, and social scientists alike have presented several approaches to explain why people like what they see. Artists must constantly concern themselves with emotional responses to specific designs and works of art. Kant argues that beauty (what he calls the "Ideal Beauty") would not be beauty at all without the context of other things that we deem as "not beautiful."[16] Beauty, therefore, becomes a measure of relative position. He further argues that much of what we call "aesthetic" has more to do with an imposed system of morality from within that our culture. But not all explanations for the manifestation of beauty were as rational as Kant. Schiller would come to contradict Kant's rational definitions of beauty with his own philosophies that included sensuousness and spirituality.[17]

This is a much different formal approach to measuring delight than that of Birkhoff (1933). While Birkhoff's system M=O/C provided the measure of complexity as it relates to individual shapes, this is rather unnatural as it does not account for the human response to a

---

[15] The architects, Denise Scott Brown and Robert Venturi, summarized that Gropius and the followers of the Bauhaus had taken on the approach that Firmness + Commodity = Delight. This was their interpretation of Gropius, while there exists no evidence that Gropius actually said this. Venturi, R., Brown, D. S., & Izenour, S. (1977). *Learning from Las Vegas: The forgotten symbolism of architectural form.* Cambridge, MA: MIT.

[16] Kant, I., & Meredith, J.C. (1952). *The critique of judgement.* Oxford, England: Clarendon.

[17] Schiller, F. (1981). *On the aesthetic education of man.* N.P.: Ungar.

given shape.[18] Birkhoff's measure of aesthetic value comes from the object's geometric configuration, but most artists' measurement of beauty comes from the observer's eyes.

For the designer it might be enough to define delight as being a product of collected values from visual experience. Aesthetic impressions can accumulate embedded meaning over time. With this framework, designers and artists must still learn to be reflective on their own musings and rationality for the things they call beautiful. How we recognize and negotiate the moments of "subjectivity" can be articulated through calculation and rules.

2.8.1 Seeing, Delight, and Cognition

Another approach to the understanding of aesthetics and delight can be found from the sciences. The neurotransmitter dopamine is naturally produced and released in the brain during moments of intense pleasure such as eating, sex, and of course play. Many scientists believe that the release of this natural drug is an essential component for human survival; it gives a primitive signal to the brain, telling it that what it is doing is right. Humans must eat to survive and procreate to reproduce. This stimulus causing the release of dopamine is internalized as a reward and, therefore, reinforces the given activity. This is also why meaningful play can be so addictive. Furthermore, with increased exposure to these phenomena, humans develop the ability to produce dopamine during moments of anticipation to the actual moment of pleasure. Most behaviorists have based their theories on this concept, and it was most notably demonstrated by the work of Skinner.[19]

A recent study from the Montreal Neurological Institute showed how listening to music can lead the brain to release dopamine in its system (Salimpoor et al., 2011). Various experiments were conducted using brain imaging to measure the levels dopamine released as well as the points in time of which it was released as it corresponded with the music. What their findings

---

[18] Birkhoff, G.D. (1933). *Aesthetic measure.* Cambridge, MA: Harvard University Press.

[19] B. F. Skinner was a very influential 20th-century psychologist. His operant conditioning concepts build off the concepts of classical conditionings shown in the work of Pavlov. Pavlov, I. P. (1927). *Conditioned reflexes: An investigation of the physiological activity of the cerebral cortex.* (G. V. Anrep, Trans. & Ed.) London, England: Oxford University Press.

discovered were unique differences in the release of dopamine as it related to anticipation and its release when actually experiencing key emotional peaks in the music. In like manner, they define the experience of anticipation as *"wanting"* and the experience of reward as *"liking."*

> *The notion that dopamine can be released in anticipation of an abstract reward (a series of tones) has important implications for understanding how music has become pleasurable. However, the precise source of the anticipation requires further investigation. A sense of anticipation may arise through one's familiarity with the rules that underlie musical structure, such that listeners are anticipating the next note that may violate or confirm their expectations, in turn leading to emotional arousal, or alternatively it may arise through familiarity with a specific piece and knowing that a particularly pleasant section is coming up. These components are not mutually exclusive, as the second likely evolves from the first, and the overall anticipation is likely to be a combination of both.* (Salimpoor et al., p. 262)

While musicians, artist, and designers may not be fully privy to the inner neurological wiring of the mind, what they do possess (and have done so from some time) is the learned ability to trigger our emotional responses.

> *Indeed, composers and performers frequently take advantage of such phenomena, and manipulate emotional arousal by violating expectations in certain ways or by delaying the predicted outcome (for example, by inserting unexpected notes or slowing tempo) before the resolution to heighten the motivation for completion. The peak emotional response evoked by hearing the desired sequence would represent the consummatory or liking phase, representing fulfilled expectations and accurate reward prediction.* (Salimpoor et al., p. 261)

Designers, like musicians, learn to arrange and reveal different moments of anticipation and surprise. They mix the mundane and ordinary with the extraordinary and unexpected. Perhaps, the release of dopamine makes us partial to novelty, originality, and uniqueness. This is also the impetus that drives so many young design students on the quest to design things that have "never-before-been-seen."

The challenge to produce original design work, in the sense that has never been seen, does not have to be as mysterious as many artists make it. We can find the element of surprise in everyday things just as much as we could find it in things our eyes have never seen. Duchamp (1917) knew this, and his "Fountain" played off this principle. Shape grammars provide a design approach that allows artists to constantly forget what they are seeing and then appreciate the work with a fresh perspective (see chapter 3). Every time we see shapes, we can find new components embedded within what is right before our eyes.

While this may seem interesting, for designers, delight is calculated with the eyes. Designers are not hooking themselves up to EEG machines to get dopamine measurements to determine aesthetic decisions. They do, however, possess a keen awareness of their own values and sometimes the values of others when it comes to visual appreciation. The methods and techniques used to reach these values need not be secretive but can be translated and taught through formal rule systems. This is what we call visual calculation, and it is far more valuable to design than scans of the brain at work.

2.9 Design and Art Education: Problems in the Classroom

In many ways STEM is the new guild system that compartmentalizes the professions into discrete categories. Although this system is not historically new, there are still striking differences between communities of science, technology, engineering, and math and the guild communities of architecture. STEM fields pride themselves with the creation and sharing of knowledge; however, the architecture and fine art guilds continue to promote secrecy and illusion to mask the true identity of acts of which the public calls "creative." For the STEM fields, transparency, the accessibility, and repeatability of shared knowledge are the key ingredients to the furthering of knowledge. In architecture, only portions of the activities occurring in the design process are made visible to both students and the public alike. The guild never delivers a formal account of creativity. It never goes into the details of ways to create delight.

This "guild mentality" plays out most dramatically in the setting of the design studio found in the professional programs of modern colleges and universities of art and architecture. Because of this architecture is faced with a hardship in trying to keep itself situated in the university as the place for training people within its field. Attempting to stay within the confines of what Schön (1983) calls *"Technical Rationalism,"* architecture maintains its distance as it makes some of its practices shared knowledge while keeping others mystical and secret.

For too long, design education has struggled with teaching individuals how to be creative. Over the years, creativity has been defined as being purely intuitive and somewhat mystical; yet, creativity is clearly expected from every student in showing mastery of design skills. This presents a problem for design students, for they are tirelessly pursuing something that no one defines for them or tells them how to learn. Donald Schön (1987) attests to this struggle in what he calls the paradox of learning new competencies.

> *The paradox of learning a really new competence is this: that a student cannot first understand what he needs to learn, can learn it only by educating himself, and can educate himself only by beginning to do what he does not yet understand.* (Schön, 1987, p. 93)

While it seems ambiguous to define creativity, educators and students alike seem universally keen on recognizing the byproducts of creative decisions or process. In truth, individuals are more comfortable in identifying when someone is being creative than giving formal instructions on how to reach that "creative zone." There is a growing concept in the field of education called *Make Learning Visible* (Krechevsky, Mardell, Rivard, & Wilson, 2013). The espoused theory states that, if educators can make visible what it is their students are learning, then they could be more effective by adjusting the learning experience to properly match the student's level of development. Alternatively, if learning is invisible, then there is no way to tell if students are more advanced or further behind the necessary place to understand the desired material.

For years, architecture and design education has been making learning "invisible" by not dealing with the nature of creativity. Instead, they come up with labels such as "tacit knowledge" to avoid dealing with the formal explanations for what it is they do (Alexander, 1964; Lawson, 2004; Schön, 1987).There are new ways of instruction that directly deal with the meaning of creativity and offer a formal process to achieve it. Shape grammars (an example I will fully explain later) use embedding and recursion to allow us to debunk the mystique of creativity while giving design students and educators a way to make learning visible.

Another problem that comes to the surface in design and art education is its individualistic approach to knowledge acquisition. Some would make the case that the design studio is a vibrant hub of collaboration and group learning. In fact, it is true that a big component of students' design process comes in the form of dialogue about their work. However, just because the studio is structured in a way in which students are working in small groups does not mean the students will automatically engage in peer-to-peer learning (Webb & Palincsar, 1996). In fact, Hackman (2002) calls this phenomenon *"co-acting groups,"* where members are working in proximity to each other with the same supervisor but each have individual projects. He goes on to say that another sign of co-acting groups not being "real teams" is the absence of co-dependence; therefore, the individual's job completion does not depend on the actions of the other members of the game.

Collaborative group learning is one of the weakest components of the architecture and design studio, and in need of improvement. Much could be learned from the practice in computer game culture called "modding." When players "mod" or modify a game they are playing, they access the source code of the game and make changes to alter various features of it. This can include the music, the way characters look or move, and even the virtual space. Players then share these creations with others to download and experience the game in a completely new way. If design studios were to embrace the culture of "moding" and hacking as a way of creation, copying and sharing could be accepted and valued as a way of being creative.

Within the design studio, rules seem not as fixed as they are in both games and other educational arenas.

> *Designing then, in terms of chess, is rather like playing with a board that has no divisions into cells, has pieces that can be invented and redefined as the game proceeds and rules that can change their effects as moves are made. Even the object of the game is not defined at the outset and may change as the game wears on.* (Lawson, 2004, p. 20)

This presents a unique paradox for both individual and group learning in the studio. It is difficult to play the game when the rules are in flux. An alternative way of looking at this problem is to embrace and utilize the temporal nature of schemas, rules, and shapes, as they are used in shape grammars.

Part of the reason for the design studio's misguided educational philosophy, that design is best learned individually, comes from the profession's perspective on creativity and originality (Lawson, 2006; Fisher, 2000; Alexander, 1964). As Lawson (2006) points out,

> *We have come, rather falsely, to associate creativity with originality, so it follows that designers selling their skill want to seem original in as many ways as possible.* (p. 234)

Prior to the Enlightenment, creativity was seen differently as artisans worked in collaborative teams under one guild. Singer describes this historic shift:

> *The artist worked in teams-on the cathedrals, for instance – and did not believe they were hired to display their individual being through creativity. The church ordained the style as well as the content of what was to be expressed, and the artist was required to submit to ecclesiastical authorities in almost every detail.* (p. 109)

When the guild systems collapsed, along with church patronage, formal educational systems like the Polytechnic and Beaux Arts gave a new sense of purpose for the artisan and the designer. Huizinga (1944) speaks of this paradigm change:

> *The Renaissance saw the main task of the architect no longer in the building of churches and palaces but of dwelling houses; not in splendid galleries but in drawing-rooms and bed-rooms. Art became more intimate, but also more isolated; it became an affair of the individual and his taste.* (p. 201)

Hence came the birth of the arts as an expression of individual talent and along with it the folk lore of the savant, the original, and the creative genius (Cline, 1998).

The myth of the talented design student as the solitary genius working in isolation is in stark contradiction to prevailing educational theories on both learning and on creativity. Fisher (2000) suggests that, if architecture is to align itself with the arts, then it should do so by modeling itself after the performing arts and less like the visual arts. *"Collaboration is the art of design,"* he states (Fisher, 2000, p. 75). While visual arts promote the notion of individual creation, it is the performing arts that *"offer a model of inherently interdisciplinary, collaborative art form"* (p.74). The design studio will never truly become a collaborative learning environment until it shakes the perspective of creativity being linked with individual talent. Students must find ways to play together.

It is true that architecture has passed through many "isms" since modernism, but the same educational strategies are still being played out today in which the profession is behaving as a guild but maintaining a different persona to keep on par with other professions, and the expectations of the university. It appears that architecture education is stuck between two systems at odds, the guild system and technical rationality. Some have tried wholeheartedly to re-orient architecture education completely into the sciences. Nicholas Negroponte, Christopher Alexander, and Yona Friedman (to name a few), each in their own way, have given much attention toward a "scientific architecture."[20] None, however, has been embraced completely or adopted widely. Some critics of their work argue that scientific and rational methods of designing are limited, or seem "mechanic." Others claim that any type of formal approach to design would seem automated or lacking a soul. Although there may be some truth in these arguments, the problem lies in trying to teach the very things that these methods are accused of lacking. The problems in the limited formal techniques laid out by architects such as Friedman should not diminish the pursuit and need of a formal explanation for design composition.

2.9.1 Vignette of Design Studio Culture

In a short ethnographic study, I documented the learning environment of a third-year architectural studio at MIT's School of Architecture. Within the school, there are five main divisions: the Department of Architecture, the Department of Urban Studies and Planning, the Media Lab, the Center for Real Estate, and the Program of Art, Culture, and Technology (ACT). Within the division of architecture alone, there are four disciplines with unique degree programs. They are Architectural Design, Building Technology, Computation, and History Theory and Criticism. With so many allied disciplines in one school, there are tremendous opportunities for collaboration and multiple perspectives about the built environment and

---

[20] Friedman, Y. (1975). *Toward a scientific architecture.* Cambridge, MA: MIT.

design. At the same time, one can have a hard time keeping up with the similarities and differences each division and discipline holds.

There were very few instances in which I observed all of the students of the studio working in one environment at the same time. There was always an overlap between those who worked in the studio, those who were busy in other classes, or those who chose to work from home. When students were in the studio, many worked with headphones on, and almost everyone worked in silence. When the silence was broken, conversations usually generated around operational information, such as specific questions around the schedule of the class. These activities show a striking divergence from what might be expected in the ideal collaborative design studio.

For students studying architecture design, their core curriculum is centered on a semester-long clas called "design studios." These classes are taught in rooms called "design studios." And the project that the students work on is often called the "design studio." Beyond a series of elective courses, students must take a total of six design studios culminating with a design thesis to complete the Masters of Architecture program. This was to be my community of study.

How do the environment and practices of the architecture design studio influence and foster creativity? Before I began searching for answers, I was somewhat taken back that I had never asked this question of myself. Having inhabited other architecture studios as both a student and as a design instructor, I realized that I would be familiar with the very environment I was seeking to study. This would present struggles on their own, common to what some anthropologist have labeled *"native ethnography"* (Jackson, 2004). Nonetheless, I began to answer this question by taking on a role as a participant observer.

There were eleven students in my studio, with one teacher's assistant (TA), Justin, whose duties included things such as scheduling, a management task, and on occasion design instruction. The studio was taught by Maria Alessandra Segantini, an Italian architect from Venice, Italy. C+S (standing for Cappai and Segantini) is the design office she runs with partner Carlo Cappai. They met when they were just students at the Instituto Universitario di Architettura in Venice (IUAV). Here, they studied under very famous Italian architects such as Aldo Rossi and Massimo Scolari. In architecture, studying under "stars of the profession" is a rite of passage that often offers its own benefits. After winning several awards and design competitions, the two opened a very successful architecture firm, and both later returned to the university in Venice as the next generation of star faculty. This semester was not Maria Alessandra's first time teaching in the US, but it was her first semester teaching at MIT. The following is a typical interaction between student and instructor.

> "Who's next?" the professor asks, as she turns in her seat looking to the audience of students behind her. The next presenting student stands and makes his way to the front of the room with his sketchbook clinched in his hand. Standing in front of the classroom, he faces the jury, a row of middle-aged architects dressed in black with black rimmed glasses, all peering at both the presenter and the large drawings to his back. At his feet there are several architectural models made of wood pieces and brown colored chip board. After a smile and an introduction, the student begins his presentation.
>
> "As you know, our site is located in Venice." He opens with an explanation of the geographical location of the project's site while using his finger to guide the jury's eyes. He points to a large color-printed site map hung on the wall behind him. Oriented with the north arrow pointing up, the drawing holds an aerial site view of the proposed. The presenting student begins to convey his design strategy about his project, pointing to several other images hung on the wall behind him.

For the first six minutes, everything appears to be typical to a public presentation of any profession that uses visual media to help convey its message. There is usually a presenter in front of a room, you have an audience that listens, and somewhere at the end you would expect a period of Q&A. This could have been a business meeting, a conference proceeding, or even a classroom lecture. But suddenly the typical norms of audience behavior are broken. As the student continues to speak, the professor stands up and enters the space of the presenting student. Without making eye contact, she walks to the wall to have a closer look at the drawings hanging before her. In one hand, she picks a model off the ground, and with her other hand she holds a black ink pen like a cigarette tapping it to her mouth. The student continues to speak, but now changes both his body positioning and directed dialogue towards the professor who is now standing beside him, still glaring at the drawings. In mid-sentence the professor interrupts with a question,

> “But what about here? I do not see that happening here?” while pointing with her pen to the site map.

From this point onward what began as a solo performance transforms into a performance of two, in which the audience witnesses the dialogue between student and professor. At times, the voices of the other jury members seated at *the* front enter into the dialogue, asking more questions, giving more insight—all adding to the spectacle. The review has now transitioned from being a session of communicating information about design ideas to a generative discussion in which new ideas are created. The professor reaches over into her bag and pulls out a very large design magazine. She thumbs through the pages and holds it up in front of the entire room.

> “Do you see that?” she asks. She points to the images and then begins to use them to make her point all while giving design inspiration to both the presenting student and the other students in the room.

The graduate studios at MIT have a listed class time of two five-hour blocks per week, but this is by no account a reflection of the number of hours spent in the architecture studio. As one student put it, “I live here; the studio is my home.” Quite often students do spend more like seventy hours a week working on their projects in this space. You can almost tell by physical description, the students who live in the studio and the ones who do not, by the accumulation of materials and trash kept on their desks. Adam, a studio “tenant,” admitted that his own piles of empty food bags and drink containers have embarrassingly invited unwanted guests of the rodent kind.

I pulled up a stool and sat beside May, a student from Korea, to see what she was working on. The previous week I had seen her project, and the models and drawings she had on this day had evolved into something else. What were once rectilinear building forms were now circular forms with smooth round roofs. I would find out that these were “massing models,” forms that occupied the space on the project site and gave the reviewer an idea of what was to come.

> “That’s quite a dramatic change,” I said pointing at a computer-rendered drawing hanging by her desk.
>
> “Yes,” she replied with a smile.

> "Is this a good change?" I followed.
>
> "I won't know until she looks at it," responded May. The person May referred to as "she" was her studio professor, Maria Alessandra.

A big component in the students' design process comes in the form of dialogue about their work. Students are constantly working under a timeline set by the studio professor in which they have dedicated moments where they must explain their work. This is done in both formal and informal settings. These moments in which students are explaining their work instead of producing it are called "design crits." But as one student pointed out to me, the design crit in itself is not entirely a breaking point in design production; it is also a method of idea generation in itself.

When a design crit occurs, it contains the verbal and visual interaction between individuals in the design studio. This interaction takes form most commonly between the design instructor and the design student. However, there are several variations of the design crit, from the most formal being a "pin up" with guest reviewers present in a public setting to the most informal being the "desk crit" where the student talking is at his or her work desk in the design studio. Students rely heavily on the design crit to continue their design process, but sometimes this hinders the process, as the instructor in this case (and in several other graduate studios) is only present twice per week. To complicate matters more, the students of the Venice studio are often called on to have crits over Skype as Maria Alessandra continues to live and run her architecture practice from Italy during the course of the semester. Although this is not uncommon among architecture schools who are striving to bring in international talent as guest faculty, it still presents a scheduling challenge as students rely on the feedback of their instructors to make their next design moves.

"It's a balancing act," one student began to explain to me. "You have to keep working and pushing on, but if you do too much you risk going too far in the wrong direction. If you produce too little, your professor might be frustrated that you have not been productive enough."

I picked up a beautiful sculpted chipboard model. The pieces were intricately cut using the school's laser cutter, a machine that takes line drawings from their computer and uses the data to cut out pieces for a model. Students then take these pieces and glue back together in physical form. The model had a unique smell to it, the smell of lit matches due to the laser's habit of leaving a crisp burnt black edge. The process to make such models is long, but creating them by cutting out the pieces by hand would have been even longer.

> "How long did this one take?" I asked one student.
>
> "Nine hours," he replied, "But I can't use it."
>
> I was shocked.
>
> "It's okay," he continued with a smile. "It was just an exploration; it's all a part of the process."

I found this to be very common in the aftermath of the design crit and the early stages of the design process. Students are constantly processing ideas through the creation of tangible material, and when those ideas get thrown out, there is a trail of leftover models, drawings, and all of the other stuff they used as tools of communication in the design crit.

The studio has a very lose structure, allowing for both real team behaviors and co-acting group behaviors to exist, depending upon the social behavior patterns of the studio's participants. As students choose their own seats, and work hours outside of the studio, I was able to see if this studio was indeed purely co-acting. Outside of the pin-up reviews (the formal crits), I never witnessed every participant of the studio in the studio at the same time. There was always an overlap between those who worked in the studio, those who were in other classes at the time, or those who chose to work from home and only appear when they had a scheduled desk crit. When they were in the studio, many worked with headphones on and almost everyone worked in silence. When the silence was broken, conversations usually generated around operational information, such as specific scheduling questions. In some cases, students discussed how their particular desk crit went, whereby they gave a detailed account, even reporting on the professor's demeanor for that day.

Research on collaborative learning environments has specified that, in order for teams to be truly collaborative, they must have collective responsibility, a clear sense of direction, and tasks that are meaningful to all of the members (Hackman, 2002; DuFour, 2003; Butterworth, 1990). Furthermore, Smith and Goldhaber (2004) point out that, in an ideal collaborative learning environment, the role of the instructor should be reduced from someone who presents knowledge into someone who clarifies information, offers questions to extend dialogue, and participates in parallel play. Ironically, these group behaviors were not seen in the studio until I re-defined what the group was. I thought I would see "groupness" in the peer members of the studio, but real teams were found only when I considered the professor and TA as actual group members and not instructor facilitators. All three had a collective responsibility, working on the design project was meaningful to each, and their task to work on this design project was definitely co-dependent. Real team and group behavior did exist between individual students, Maria Alessandra, and Justin (the TA).

Individuals of the studio working in these "mini-groups" seemed productive in spite of the clear imbalance of power due to the leadership structure. Leadership, as defined by social scientist, has less to do with the characteristics and traits of an individual and more to do with the influence or power that influences people or groups interpersonally. Schmuck and Schmuck (1992) give a consolidated list of seven bases for the influence of power, which are: expert power, referent power, legitimate power, reward power, coercive power, informational power, and connection power.

Before it even occurred to me that this form of "groupness" was taking place, I asked Maria Alessandra what her role as the studio instructor was.

> "You have to be sensitive to each student's ideas," she told me. "Each student is unique with experiences. Students can start generating their ideas from wherever; my goal is to guide them through developing their logic."

Although Maria Alessandra's desire as an instructor is to displace her power to the members of the studio, it is very clear that, due to her "expert power," students seem more willing to let her navigate the ship. "I chose this studio because I wanted to learn HER design process," one student told me. Another informed me that she chose this studio because of Maria Alessandra's background as an Italian and as a woman.

Students have a clear perceived hierarchy on whose voice they listen to throughout their design process. "I'm constantly talking to people about my project," one student told me. They talk to peers, members of other studios, sometimes other faculty, and of course the crits that include their professor, TA, and periodically outside jury members.

> "With all of these voices, including your own, how do you know which one to listen to?" I asked one student late in the semester.
>
> "Right now, Maria Alessandra's," he responded laughing.

I went into the design studio optimistically looking for playful engagement. I thought that playing would exist between clusters of the student members of the studio. The clustering I discovered was of the student, studio professor, and TA. This was the actual boundary of the magic circle. Peer-to-peer reliance was absent from the design process. Students were comfortable working in very hierarchical group settings, and in the end the lack of democracy did not seem to thwart the creative process.

It was late in the semester and Maria Alessandra was finishing a desk crit with Jin, one of the older design students who had a previous background in architecture before coming to MIT. The week before, there had been a pin up, and he had told me he was very pleased with how it went. The two were sitting at his desk ending what seemed to have been a very long conversation.

> "What should I do?" Jin asked.
>
> "The important thing is to manage the middle scale. Consider the landscaping and how it translates into space. The middle scale is where you test things; it's where people touch and where people gather. You have to take a position on that," Maria Alessandra said.
>
> "So do you have an idea of how I should do that?" asked Jin.
>
> Getting up from the stool, Maria Alessandra smiled, "I don't know. It's your project."

As this example illustrates, the educational philosophy on the role the instructor takes in the design studio contains much contradiction in the *espoused theory* of practice and the *theory-in-use*. On one hand, the design studio is said to be a *constructivist* learning environment, where the end solution is never in sight and the design students learn through inquiry. Those who espouse this theory go as far as to say that design is something that cannot be taught (Allsop, 1952; Eisner, 2002). Other perspectives of the design studio show very clearly an *objectivist* model of learning, where knowledge on design is transmitted from instructor to student (Roblyer and Doering, 2010).

In the design studio, these two educational philosophies are always in tension; in some cases, they are both active, existing in contradiction. The Bauhaus model of the design studio clearly recognized that design was not something that could be taught "top-down."[21] Ellen Langer (1997) in *The Power of Mindful Learning* talks about the top-down versus "bottom-up" approaches to teaching. Top-down approaches rely on discourse, lecturing to students, and would be what she calls *"mindlessness."* The alternative path in what she calls *"mindfulness"* is the bottom-up approach which follows along the experiential methodology of learning as championed by Bruner, Dewey, Rogers, Montessori, and Gropius, to name a few.

Although the Bauhaus was great for solidifying constructivism in the design studio, it also carries much of the blame for the seeds of objectivism that we see in the architecture studio. Students often expect from their instructors explicit direction and design knowledge. The attention paid to "star designers," the re-embodiment of the guild system with its master-apprentice relationships, were all instituted by the Bauhaus and can still be seen in the studio today (Fisher, 2000). Design juries, a tradition stemming from both the Beaux Arts and Bauhaus, personifies objectivism. Students look to these perceived outside "experts" for confirmation and assessment of their design decisions. Schön's example echoes this in the depiction of Quist, the studio professor, and Petra, the design student. It shows Petra learning by watching her instructor "re-frame" the design problem through a series of dialogue and sketching (Schön, 1983).

However, Schön tries to break the instructor away from the image of the "master" to that of the "coach." In *Educating the Reflective Practitioner,* Schön (1987) points out good coaches are constantly trying to discern what the student understands while students are trying to

---

[21] In larger measure, shape grammars are agnostic in this debate – applying to constructionist and instructionist approaches.

decipher what the coach is trying to demonstrate and describe. This is very similar to the before mentioned *zone of proximal development* created by Vygtosky.[22]

From another perspective, we can criticize that the coaching might go too far. Schön points out that one common mode of knowledge transfer in the studio is demonstrating and imitating. Coaches demonstrate, and the student imitates. In this process, the imitator has to both observe and reconstruct. Whether or not this is an effective teaching strategy truly depends on the student. The student can either mindlessly copy, falling into automated - rote behavior (Langer, 1997), or the very act of copying can lead the student to see the project in a new way (Stiny, 2006). Copying done mindfully is a key component in being creative.

---

[22] Vygotskiĭ, L. S., & Cole, M. (1978). *Mind in society: The development of higher psychological processes*. Cambridge, MA: Harvard University Press.

Chapter 3

Shape Grammars and Visual Calculation

3.1 Multiple Intelligences, Multiple Ways of Calculating

When we hear the word "calculation," what often comes to mind is its application in mathematics. We think of numbers, operands, and the painful memories of memorizing multiplication tables. While mathematics does have a relationship with calculation, mathematics is only a subcategory of calculation and not vice versa. In fact, there are many ways to calculate that do not involve numbers or mathematical functions. The game I designed and used for this research (simply called the *Shape Game*) is based on the idea that we can calculate with our eyes. As I hope to demonstrate through this research, calculating with your eyes is very helpful to individuals wishing to approach visual arts and design from an algorithmic perspective.

Calculation, broadly understood, has three components: variables, a computation process, and a yield/outcome. In mathematics, we understand variables as numbers; for algebra, we use letters as abstract place holders to represent the variables used in the computation process. Variables, in any calculation system, are the building blocks and starting points for computation to occur. Without establishing variables, we cannot move to the next critical component of calculation, the computation process.

A computation process is an operation (or set of operations) that acts on the established variables. We might even think of these as rules, commands, or instructions that tell us what to do with the variables. Using mathematics, again we learn early on about addition, subtraction, multiplication, and division and use them as the foundation for much more advance computational procedures. In linguistics, we may look at the rules for developing proper sentence structure. While speech has its own set of rules, written text likewise has a set of operations that dictates how a person should communicate properly with words.

The output of variables gone through a computational process eventually produces a product. The product in mathematics may be the sum result of numbers added, or in linguistics a proper sentence may result by the correct placement of nouns, verbs, and punctuation. In all calculation, the rules applied to the variables give results that are then accepted or rejected by the individuals performing the calculation. If results are rejected, they simply go back and begin adjusting the computational rules or change the initial variables. Calculation in the broadest sense is not a linear process that looks for a single correct solution; calculation is a way of doing.

Understanding calculation as a process relies heavily on thinking in systems and promotes algorithmic thinking. If calculation is a way of doing, the algorithm is the description of the entire calculation system. Identified as a 21st-century skill, systems thinking and algorithmic thinking have a place in both traditional STEM domains as much as they do in the arts. This broad understanding of calculation is very useful in learning the fundamentals of any object-oriented programming language, but also offers artists a new way to be insightful in their practices.

Society has placed a high commodity on individuals who show high proficiency in mathematical and linguistic calculation. In fact, math and verbal skills are most sought after by universities that look toward standardized testing as a measure of the overall intelligence of the individual. This is made explicit in several universities by their entry requirements for SAT verbal and math scores. In the late 70s, Howard Gardner, a researcher at Harvard University's Graduate School of Education, began to challenge the notion of measuring human intelligence by only math and verbal skills.

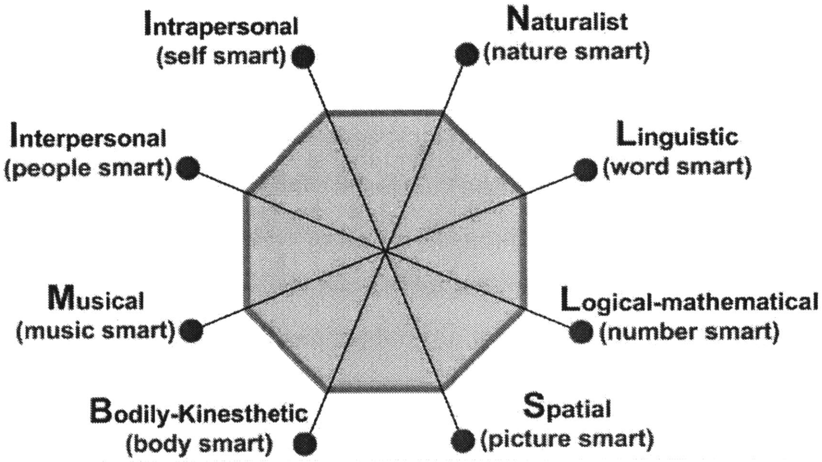

Figure 3.1: Gardner's multiple intelligences

In the *Theory of Multiple Intelligences*, Gardner (1983) identified nine different intelligences humans possess: linguistic, logical/mathematical, spatial, rhythmic, kinesthetic, existential, naturalist, interpersonal, and intrapersonal. Furthermore, he also recognized the computational components that can be readily seen in anything we define as human intelligence. Gardner (1983) writes,

> *One might go so far as to define a* ***human intelligence as a*** *neural mechanism or* ***computational system*** *which is genetically programmed to be activated or "triggered" by certain kinds of internally or externally presented information.* (p. 64)

If human intelligence is indeed a computational system, then we can look for the three components of a calculation system within any of these nine intelligences.

Spatial intelligence is most often linked with individuals in the visual arts (Gardner, 1983), but we can argue the presence of several other intelligences at play, depending on the artists and the medium in which they work. Jackson Pollock, for instance, was dealing with spatial intelligence skills while demonstrating a unique command of the kinesthetic.[23] Since it is impossible to identify each of the intelligences used by visual artists (arguably all may be used at some point), the aim of this research is to demonstrate the calculation components most pertinent to the visual arts.

The shift from thinking about visual arts (or any art form) as being a product of giftedness to that of a computational system is critical in the transformation of K-12 arts education. By doing so, it may attract students to the arts who previously have shied away under the assumption they were not born visually creative. A major contribution to this new way of looking at visual art is how it places both system thinking and algorithmic thinking within the domain of the arts. Traditional STEM subjects have gotten much of the credit in developing these skill areas. If we broaden our understanding of calculation to see its manifestation in the arts, we can help bridge the divide that has stood for so long between these different subject areas.

---

[23] Naifeh, S., & Smith, G. W. (1989). *Jackson Pollock: an American saga.* Clarkson N. Potter.

3.2 Seeing and Calculating

With every action of the design process, we are calculating. There is calculating for firmness, calculating for commodity, and even calculating for delight. The ways in which we go about calculating are the very steps that define the process of design and should be the very focus of instruction within design education. However, teaching with a pedagogical stance that gives formal explanations to what has previously been considered unquantifiable comes with much criticism. Those who identify themselves with the business of traditional calculation (mathematicians, logicians, computer scientists) perceive design and the arts as subjective and irrational. Designers, architects, and artists perceive design methods that embody calculation methods as limiting, lacking emotion, automatic, and a hindrance to "creative expression." Christopher Alexander (1964) notes this in the *Synthesis of Form*,

> *Logic, like mathematics, is regarded by many designers with suspicion. Much of it is based on various superstitions about the kind of force logic has in telling us what to do.* (p. 7)

Visual calculation utilized through the methodology of shape grammars provides the unifying arrangement that situates design between being an intuitive artistic expression and being a formal system of calculation. Shape grammars with their schemas and rules provide both algebraic and graphic blueprints that can be descriptive or generative in use. When applied, shape grammars are not fixed, but flexible allowing for emergence as new shapes and rules can be introduced effortlessly at any time. Embedding and recursion provide a fluid, intuitive, active way that invigorates design and illuminates the "play element" in the design process.

In "What Rules Should I Use?" Stiny (2010) addresses the title question with a short but precise answer, *"Use any rule(s) you want, whenever you want to"* (p. 15). The answer that relies on intuition and personal input is far from the assumptions many presume about computational methods of design. While some researchers are looking for "rhino scripts" and one-click solutions to produce artificial creativity, shape grammars rely on the human eye in the design process. Shape grammars do not tell you why you should use any particular rule, what rules to use, or even what sequence to use them. They do, however, present a way to calculate, a way to design and to talk about design, and a way to think reflectively about what you are doing for inspiration to move forward. Through recursion and embedding, shape grammars are the gateway to creativity.

3.2.1 Shape Grammars

First introduced by Stiny and Gips (1972), shape grammars have become a field of study in their own right, used by designers, architects, and artists alike. In use, they can be generative or descriptive, allowing the artist to create artwork and communicate existing works of art through a formal language. Until now, there has not been any exploration using shape grammars in K-12 art and design education. As we begin to integrate more digital technology into K-12 curricula, this research becomes critical in sharing the benefits of this algorithmic approach. It provides us a more mindful way to think about new tools and gives insight on how to create new tools for future use.

Shape grammars have three components: *shapes, shape rules, and shape schemas* (Stiny and Gips, 1972; Stiny, 2006). Shapes can be anything! There are "0" dimensional shapes (points), 1D shapes (lines), 2D (closed shapes or planes), and 3D shapes. The shape variables can also be a combination of individual discrete shapes that are nested together. Once they are nested, the discrete nature of these shapes is lost as the lines and subcomponents fuse into each other. The most important property of this type of variable specification is that it is never fixed and can transform through the application of a simple rule.

Shape rules are expressed similarly to mathematical functions having variables that follow a function arrow into a new state. Instead of using the lettered variables (x, y), shape rules use the graphic image of the shape specified as the initial variable. The shape variables can take any form specified by the artist.

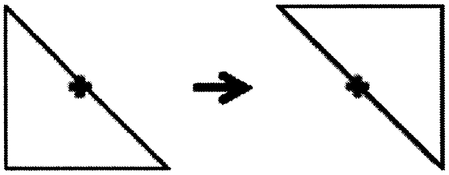

Figure 3.2: Shape rule using the graphic image of the shape specified as the initial variable with function arrow

The function arrow communicates the transformation applied to the initial shape variable (Figure 3.2). Transformations applied to the shapes are identical to the geometric transformations found in mathematics. There are Euclidean transformations that consist of translation, rotation, and reflection. These three are also known as isometry; they are transformations that do not change dimensions of the base variable but keep it congruent. In addition to these three transformations, we find scaling that can occur both uniformly and parametrically.

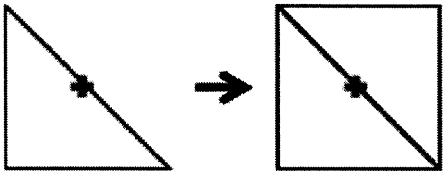

Figure 3.3: Shape rule making a copy of the initial shape and then rotating the copy

Shape rules can also communicate the deletion of shapes (or shape components), the addition of new shapes (or components), as well as the identity rule that keep shapes the same. Shape rules can be combined in multiple ways to make statements requiring more than one action. For instance, if we wanted to write a rule that make a copy of the initial shape and then rotates that copy, we could write it as in the example shown in Figure 3.3.

The rule is first using the right triangle and applying the identity function to keep the initial variable. The rule is then taking a copy of that shape and rotating it 180 degrees around the label position (+). It should be noted that this rule might also be interpreted as a reflection transformation about the hypotenuse of the original triangle. The result of the applied rule causes the emergence of the square shape. While the square was not an original variable defined by the artist, we can clearly see it in the result of the applied rule. The designer can now apply rules to the found square or perhaps create new rules that apply to the initial triangle variable.

Once designers have a collection of rules, they can apply them in any sequence they desire. The shape grammar then is the set of rules and variables used in the series of created art work. The users are free to apply the rules in any sequence they see fit, and each unique piece of work is then in the "language" of that grammar. Artists are always free to add or delete both rules and variables in the grammar. In this way, artists are manipulating the grammar in use which, in turn, begins to augment the end product.

While the generative usage of shape grammars is helpful to create blueprints to begin a single piece or body of artwork, the descriptive properties of shape grammars are helpful in discussing artistic styles. Most conversations around artistic style center on the technique and motivations of the artist. What was the artist trying to convey? What technique did the artist invoke? While these are helpful conversations to understand works of art, they say little about what our eyes actually see. The visual description of works of art is rarely explicitly discussed and never talked about on the level and detail that shape grammars allow in describing a composition. This new layer of understanding only broadens the discussion of visual art and, most importantly, brings new individuals to the conversation, such as the computer scientist and algorithmic-minded individuals. Likewise, children are presented with multiple entry points to the visual arts.

Shape rules give a recipe for the masterpiece. The intent is not to communicate what the artist was thinking, or even the artist's direct path to their finished piece of work. Instead, shape rules present a formal way to understand the visual qualities of the work. In the same way mathematicians and scientists write formulas to model real world phenomena, through shape grammars we can look at art through a succinct formal description.

Although shape grammars present an abstract way to visualize a piece of art's inherent system, it is the abstraction itself that makes it most appealing to artists. Sketches are abstract representations of things that exist either in the real world or in the mind of the artist. The sketch does not pride itself on accuracy of information as much as it does interpretation of information. If all we wanted was accurate data of physical artifacts, we could create a digital scan, take a photograph, or use an array of new digital tools that are at our disposal to collect the information. However, hand-drawn sketches attempt to internalize what the eye sees and interpret what's expressed.

This expression is an abstraction of what is actually there. The abstraction is selected by documenters with a purpose to emphasize things they find important. As a result, line weights, texture techniques, color, and even notation are introduced to tell the story of what documenters are seeing in their minds. Likewise, shape grammars, when used to describe existing works of art, do not attempt to communicate exactly what artists were thinking at the time of creation. Rather, they provide a useful sketch to the documenter to be used in further work. Shape grammars capture these ideas in a formal system that gives opportunity for future inquiry.

Visual calculation carried out by a shape grammar-like approach to artistic compositions provides the unifying arrangement that situates the arts between being an intuitive expression and being a formal system of calculation. Shape grammars with their schemas and rules provide both algebraic and graphic blueprints that can be descriptive or generative in use. When applied, shape grammars are not fixed but flexible, allowing for emergence as new shapes and rules can be introduced effortlessly at any time with schemas. Embedding and recursion provide a fluid, intuitive active way that invigorates the creative process and illuminates the "play element" in the art creation.

In summation, playful calculation allows for:

1) Flexible vision (identifying constant, changing variables or units)
2) Rule processing (creating and following algorithmic rules)
3) Emergence (discovering and generating embedded variables)
4) Recursion (parametric rule application)

3.2.2 Shape Rules and Play

The importance of "play" in design education has to do with play's ability to bring out creativity. It is impossible not to be creative while in a state of play. One might say creativity is the very thing that is framed by the boundaries of the magic circle. We can safely say that play and creativity have a strong correlation.

Play = Creativity

At the same time we have already shown that creativity contains recursion and embedding. Recursion and embedding, as shape grammars have shown us, are copying with a purpose. We can then state,

Recursion + Embedding = Copying

and,

Copying = Creativity

If these are true, then copying, by definition, is in fact being in a state of play and a state of creativity all the same.

Copying = Playing

When individuals are copying, it's easy to see that they are indeed in the "ludic state," a state of play. As Stiny (2010) states, *"Embedding lets me copy without copying by rote—there are no building blocks—in a kind of visual improvisation that's full of surprises. Anything can change anytime"* (pp. 29-30). What allows shape grammars to be such a strong agent of play are their requirements for designers/game-players to constantly use their eyes. It is a game of seeing that corresponds to rules. Play takes players into a mode of thinking and behaving that allows them to behave differently than if outside this *"temporary world described by play."* Within the magic circle of play, a broom can become a horse, a stick can be a sword, and people are in a heightened state of imagination and creativity.

Within visual calculation, play occurs by allowing designers the freedom to see, create, and change rules at any moment through schemas. However, when designers subject themselves to a specific grammar system defined by a discrete set of rules, play begins to evolve into "game play." Games are special instances of play that are formulized and bound by a set of rules (Salen and Zimmerman, 2004). Design games evolve out of playful activities and, in turn, set the conditions for a new type of play and, in doing so, require focused creativity from players.

An example of this type of ludic behavior through shape grammars can be seen in the *Kindergarten Grammars* described by Stiny (1980). The kindergarten grammars are an extension to the Froebel building gifts made popular by architects, such as Frank Lloyd Wright. Within this system, shape grammars work with a kit of parts and configurations, serving as the vocabulary and a category system that together make the language of design. Just as it is in all game play, the constraints of the system bring out the play element. In doing so, they produce creativity. While kindergarten grammars are combinatory in nature, they still demonstrate the ludic offerings of shape grammars. When designs move beyond combinatory systems, we can move beyond 0-dimensional elements to allow for more "play moves" that include embedding and shape emergence.

A pre-shape-grammar version of the kindergarten grammars has been adopted and used in the design studio since the early days of the Bauhaus. The "nine-square" design project is a common exercise given to students in the Beginning Design curriculum. Within this exercise, students are forced to work in complete abstractions. Love (2003) writes *"By reducing possible design solutions to reductive elements like 'walls-as planes' and 'piers,' students were encouraged to think about spatial relations"* (p. 44). Unlike shape grammars' explicit usage of rules and vocabulary, these design exercises focus solely on the kit of part pieces. This can be problematic for several reasons.

While this exercise does provide students with a scaffold introduction to thinking about form and space, there is no guide or system put in place to lead students on what to do. It is as if the students are playing a game, without knowing what moves they can take. Terry Knight (1994) points out,

> *Artist and architects do invent and play abstract design games, and one of the challenges of understanding styles and their evolution is confronting and understanding the rules of these games.* (p. xv)

They see the chess pieces before them but haven't a clue on the different possible actions available for them to take. Of course, the shape grammarian has an answer to this, "Copy!" Evidence exists that copying is what most students end up doing, if not from their peers (done secretly), from examples put forth by their studio instructor. If shape grammars could take a more prominent role in the design studio, then copying would be both practiced and celebrated as a creative playful activity.

The second problem with the kit of parts exercise is the 0-dimensionality of the game. Each component in the kit of parts exercise is treated as a single discrete element, as a point. Pieces cannot fuse together nor can they be broken. There is no embedding in the general sense and, therefore, no emergence of new shapes, as the set of pieces in the kit of parts represent the entire universe. While this is definitely a form of play, it is only one instance of the offering of shape grammars and visual calculation. The 0-dimensionality of the kit of parts also manifests itself in projects that utilize parametric design and building information modeling. This Lego-like approach to design in the end is limiting and offers fewer possibilities than traditional pen and trace paper. If designers would like to play within the confines of 0-dimensionality, they should do so knowingly and not with the illusion that they are working within an infinite set of parts. Ideally, studio design exercises should allow students to play within the upper limits of multi-dimensional shapes to account for embedding, recursion, and emergence of new shapes.

The benefits of enhancing play in design education through shape grammars are several. One benefit worth mentioning is the way shape-grammar-game play encourages designers to take risks. Games and play have a wonderful way of promoting risk-taking when players are in the magic circle. Langer notes risk-taking as being a key ingredient in being mindful.

> *Ironically, although work may often be accomplished mindlessly, with a sense of certainty, play is almost always mindful. People take risks and involve themselves in their play. Imagine making play feel routine; it would not be playful. In play there is no reason not to take some risks. In fact, without risk, the pleasures of mastery would disappear.* (Langer, 1997, p. 44)

Shape grammars promote risk-taking in their application through the security they provide for players in knowing what moves they have made and what possible moves they can make in the future. Schemas and rules provide a great sense of direction in the design process and, as a result, encourage designers to be more experimental, as they have a clear, formal explanation for their design moves and actions. When young designers have no system to inform their course of action or reflect on previous actions, they have a tendency to get lost. Design decisions, then, become random, and the designers are constantly looking for sources of inspiration and validation for their design decisions.

In the same way that shape grammar game play encourages risk-taking, it also promotes divergent thinking. A key trait of creativity is for one to have the capacity to hold a multi-view perspective on any given situation (Langer, 1997). When students are working on projects in the design studio, there is a pattern of activity in which they look at the design problem, imagine alternative solutions, implement changes, only to see new problems arise. Schön (1983) calls this the *"reflective conversation with the situation."* Schön also notes that the experienced designer has the ability to "reframe" the design question. He illustrates this in his narrative about Quist, the design professor, and Petra, the design student. In Schön's example, Quist has the ability to help his student who is stuck on a specific design problem. Instead of continuing to wrestle with the problem, Quist decides to see the problem in a new perspective, thus reframing the question to demand a new set of actions. Eisner (2002) refers to this same phenomenum as *flexible purposing, "the ability to shift direction, even to redefine one's aims when better options emerge in the course of one's work"* (p. 77).

Shape grammar design methods are all about flexible purposing. Embedding is generous; it allows you to see whatever you want to see in terms of rules. While schemas give suggestions on rules to see a particular design, they do not lock you into seeing the design in any fixed way. This makes calculating a natural form of visual play. When you look around, you see new things all the time; your eyes trace, flip, and manipulate shapes on a page unlike the discrete binary way of seeing our computers use. Shape grammar game play requires "multi-vision" to play the game successfully; the more ways you see, the further you advance in game play.

Finally, shape grammar game play encourages collaboration in the design studio. A flaw in the current practices of the design studio is the individualization in the completion of the creative task in the design process. In short, students do not play together. On the surface, there does seem to be collaborative effort, but these exercises are usually non-creative tasks. As pointed out in the AIAS Studio Culture Task Force,

> *Group projects are most often limited to pre-design activities of research, analysis, and site documentation. The synthetic processes of design, in which negotiation and collaborative skills are most critical and difficult, are limited to individual efforts.* (Dutton, Koch, Schwennsen, & Smith, 2002, p. 12)

Shape grammar game play's embrace of a culture of copying would be a remedy to the individualized nature of traditional studios. In current times, it is taboo to "copy" a colleague's work, but as we have already proven, copying is both being creative and playful all in the same. Many of the reasons students do not collaborate is a fear that a peer might "steal" their ideas (Hu & Chen, 2006). In shape grammar game play, "stealing" is the name of the game. Students would be encouraged to share and copy from each other's design rules and schemas. Embedding and recursion would occur in designs that would extend the individual's drafting table to any in the entire school. As the culture of mindful copying would increase, creativity would with it.

3.3 Shape Schemas

With shape rules we use graphic representation to communicate the desired transformation of a variable, but shape schemas maintain a traditional algebraic expression to communicate the executed transformation. Shape schemas are intentionally abstract, as they give very general descriptions of the rules in play. In developing shape grammars, Stiny (2006) identifies a set of generic schemas that are commonly used in artistic endeavor.

For instance, we can write the schema.

$$x \rightarrow t(x)$$

This schema describes the transformation of a specified variable x, as seen in the rule shown in Figure 3.2. The transformation used in the schema is not specified and can refer to any of the aforementioned geometric transformations (translation, rotation, reflection, and scaling). Building on this, we can expand this schema as,

$$x \rightarrow x + t(x)$$

This schema describes an action that keeps the initial variable x, but then copies that variable and transforms the copy to a new spatial arrangement, t(x), as seen in the rule shown in Figure 3.3.

Shape schemas are like mathematical models that help describe an overall system. Mathematical models have been used to describe systems for years and offer great affordances in explaining how things work or come together. Playing with them promotes algorithmic thinking, as artists begin to think about their work as a system. Computational rule building introduces a new way to describe the qualities of an artistic composition's system. There are many qualities that make up the entire system of a given piece of art. Among them are visual quality, visual perception, and materiality. Shape grammars are a clear way to express this system.

3.4 Parametric Euclidean Transformations

$x \rightarrow x'$ is the schema that describes the parametric transformation of a shape. Parametric rules have been at the forefront of Building Information Modeling (BIM) strategies as well as several of the digital tools previously described in *alea* play. The ability to describe a set of possible transformations that all can be classified under the same schema can be very helpful to designers.

Shape grammars almost always rely on the spatial relationship of shapes on some dimension greater than zero. When we create the shape rule, this is done by applying some transformation of the initial shape to its established new position. Sometimes, it is helpful for these transformations to fall within a range of possibilities instead of having a fixed transformation. In the same way we are flexible with our eyes on what exactly we specify as the shape in use, we can be flexible on the way the transformation is applied.

Establishing a range of actions instead of a single action is the equivalent of creating the boundaries of the magic circle encompassing play. When we create or play games, we understand the game by what we can or cannot do in that game. Rules of a game often establish common moves, and illegal moves, but then leave the range of possibilities (or everything in between) up to the players to discover in the act of playing it. In shape grammars, parametric transformations are the way to achieve finding the range of action applied to the shape. If we can identify a range of possibilities and establish the boundaries of that range, we can find diffeent scenarios within that set.

3.5 Algorithmic and System Thinking

Is there a major difference between visual thinking and algorithmic thinking? Algorithmic thinking is a fairly new term coined out of the fields of computer science, and brain and cognitive research. The premise behind this term is there is a base set of mental abilities that an individual must develop prior to mastering a computer language. Mastering the proper syntax of a specific computer language is a skill in itself and is developed over time, but most educators believe that algorithmic thinking is a higher order of ability necessary to learn multiple computer languages and use them to solve complex problems.

G. Futschek (2006) suggests that the abilities defining algorithmic thinking include:

1) the ability to analyze given problems
2) the ability to specify a problem precisely
3) the ability to find the basic actions that are adequate to the given problem
4) the ability to construct a correct algorithm to a given problem using the basic actions
5) the ability to think about all possible special and normal cases of a problem
6) the ability to improve the efficiency of an algorithm

This list is missing what shape grammars and visual calculation additionally have to offer:

1) the ability to analyze a problem that constantly changes
2) the ability to find new actions based on the basic actions
3) the ability to construct an algorithm flexible enough to respond to the change of the given problem

Designers know that the process to a solution is not a linear one. This is also why they often reject algorithmic approaches to design in the thought that these methods are fixed and rigid. If we keep to the above abilities specified in the computer science definition of algorithmic thinking, these designers would probably be right. Visual calculation shown through shape grammars allows for an expanded view on algorithmic thinking that is flexible, allowing for the user to take into account a larger set of known and unknown factors.

Education today puts a lot of stress on 21st-century thinking skills. Since algorithmic thinking is high on the list, visual calculation can easily take a seat adjacent to it. There is not much difference between the two. Furthermore, shape grammars allow for the development of the same abilities outlined in algorithmic thinking in a way that is easily adapted for visual thinkers, artists, and designers. In time, mathematicians and engineers may also see the usefulness of shape grammars to deal with aesthetic problems. Engineers may even find visual calculation to be a superior way to approach traditional problem sets.

Chapter 4

Calculation Found in Play

Various modalities of calculation are informally active in the play of children. Revisiting Caillois' taxonomy of play (*agôn, alea, mimicry,* and *ilinx)* we can understand each category of play as a different method of calculation. *Agôn,* is play that is competitive. When one is in competition they are aware of their opponent and make moves based upon what the opponent is doing. So the diagram describing the calculation maneuvers for *agôn* requires the transformations of the player's action based on the seeing and interpretation of the opponents actions.

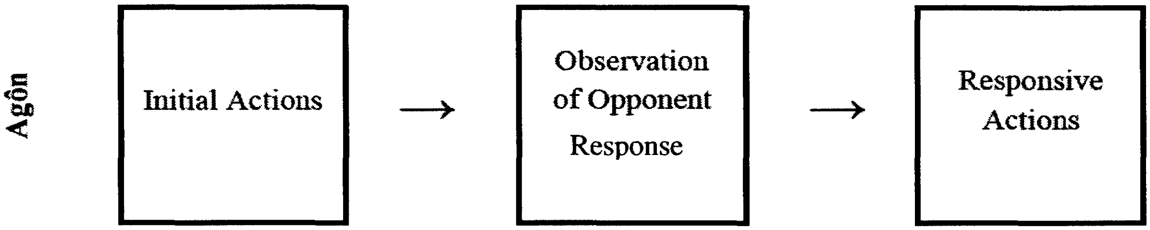

Figure 4.1: The calculation maneuvers for *agôn*

Alea is the game of chance. The play rule that embodies an element of chance requires a random selector to generate one variable from a set of possible variables after each turn of play. In essence, the transformation of the dice falling to the table, although random, still has only one of six possible outcomes. The set of possible outcomes may be seemingly large when dealing with multiple dice or other games of chance but is, nonetheless, a quantifiable collection of possible maneuvers. Computer-based games of *alea* have a great way of masking this fact due to their ability to crunch seemingly infinite amounts of data sets for possible outcomes. This, of course, is no longer valid when one is in *alea* with material that is non-combinatorial. As an example, one cannot simply quantify the number of possible compositions a pen can generate on a page, due to the ability of lines to be embedded in others.

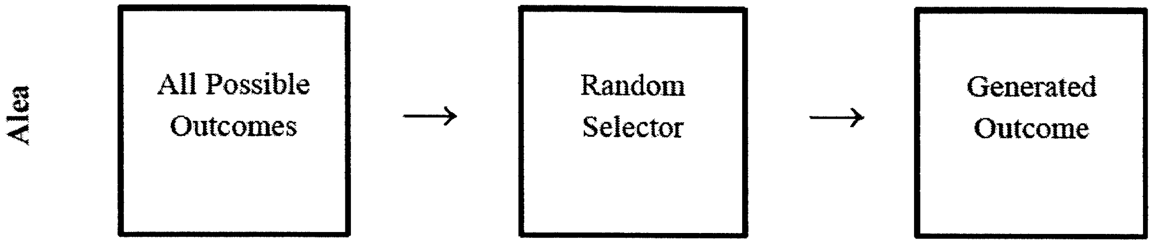

Figure 4.2: The play rule for *alea*

The game of *mimicry* has a system similar to that of the game of *agôn.* In this, the player conducts actions based on the actions of an observed source. The source then becomes the basis of the copied actions of the player to then continue the loop. This copied source may be mental projections (as in the case of children's pretend play, acting out a story they heard).

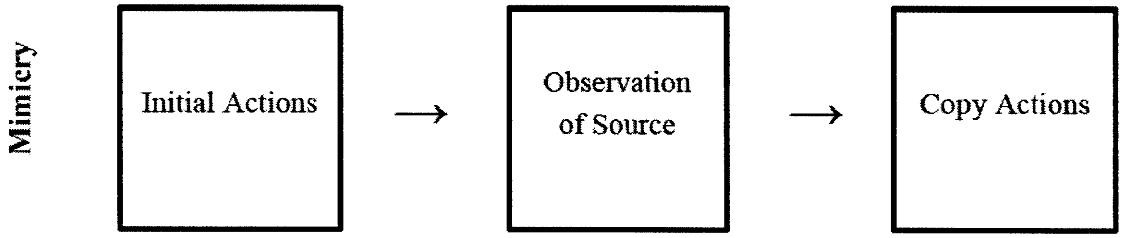

Figure 4.3: The play rule for *mimicry*

Calculation found in *ilinx* presents a model of action in which the player is affected by some variable labeled "perception disruptor." The disruptor can be an independent entity with its own controls, or it might be directly controlled by the players themselves. In the case of children spinning themselves dizzy, they are themselves the perception disruptor. In the example of *ilinx* found in looking at embedded lines, we find the perception disruptor in the fabric of the actual material. In this game the player is constantly going through the stages of being oriented and disoriented. Ilinx is applied to all of the categories of play when shape grammars are used.

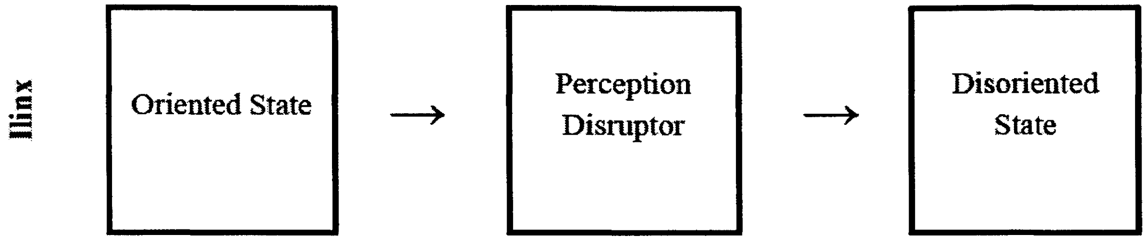

Figure 4.4: The play rule for *ilinx*

4.1 Play Grammars: A New Description of Play

"Play" continues to be researched from many different angles, but little has been done in developing a formal language to describe the process of creating play. How does one create a new game or play activity in the first place? This can be useful to both anthropology studies and to play designers who wish to create new games. Jesse Schell's *The Art of Game Design: A Book of Lenses* (2008) is relatively new but has become a go-to book for many game designers. Although it is heavily focused on the genre of video games, many of the principles covered are helpful for game designers of any genre. Schell spends a great deal of time laying out the elements needed to create his definition of a successful game. However, he never talks about the explicit evolution of one game into another. He does not talk about how designers copy from each other and from past games to develop new models of play.

I suggest the use of schemas to describe various aspects of games. We can think of these as "play grammars." In the same way shape grammars are used descriptively and generatively for art and design, play grammars can be very helpful in describing various aspects of play. They may also serve as a helpful tool to design play activities and games. Consider play interpreted as a shape, x, whose boundary defines the magic circle. We can use the following schemas impressionistically to define what happens in the creation of a new game or play activity:

$x \longrightarrow t(x)$ is where we see the transformation of play actions

$x \longrightarrow b(x)$ is where the boundary of the magic circle is the focus of play

$x \longrightarrow prt(x)$ is where play is decreased within the play system

All games and play activities can be reduced to the actions needed to play. The dimensionality of the game is equivalent to the relationship of actions embedded in the play. We can think of these actions as similar to the relationship of points, lines, planes and volumes. A play activity with the dimensionality of "0" (a point) would have one action. For instance, staring at clouds in the sky as a playful action would have a dimensionality of "0" because it has only one action. Doing the same activity, while asking children if they could spot the "elephant in the sky," would increase the dimensionality of this play activity. Now, you are engaged in multiple points of play. All of the activities that happen between these two points create the one-dimensional line, and the two major activities create the boundary of this play.

It is easy to understand how we can begin to build up schemas based on the model of analysis for play and games. We can now have a formal way to express how parts of games are reminiscent to other games and how play can evolve into new dimensions of play. As the play designer (or researcher) begins to use these schemas, the grammars of play can replace older systems of classification.

4.2 Abstract Objects, Interpretation, and Play

A *playful calculation* perspective on children's pretend play is much richer than the simple diagram of the loop of *mimicry*. What we see goes beyond the *Vygotskian* model of placed meaning. In pretend play, we find the use of rules, embedding, and emergence applied to found objects. Rules and embedding create the conditions to signify the object's meaning. Take a look at this short vignette of my daughter's play as an example.

Like most parents, I really get a kick out of watching my children play. My oldest child at the age of four is a passionate player and throws herself completely in the spirit of whatever she is playing. Taylor loves playing with sticks, but what she does with a stick once she finds it is most amazing. After wondering around the playground, she finds a stick she really likes and brings it into her play with the first transformation. The stick becomes a make-believe musical instrument, a trumpet to be exact. Placing it to her lips, she begins to make trumpet noises while marching around the playground. After a while, she takes the stick and taps it on the ground and says, "Attention!" The same stick that was moments ago a trumpet is now the conductor's baton as she waves it in the air before the imaginative orchestra. She waves the stick back in forth. Marching around the playground, the stick suddenly becomes a sword as she begins fighting off pirates. Over the span of forty minutes, I watched this stick take the form of a baton, trumpet, saw, shovel, shovel, sword, oar, torch, and spoon. With each embedded meaning, she was completely engaged in a narrative play of make-believe that hinged on her interpretation of the stick which she held in hand.

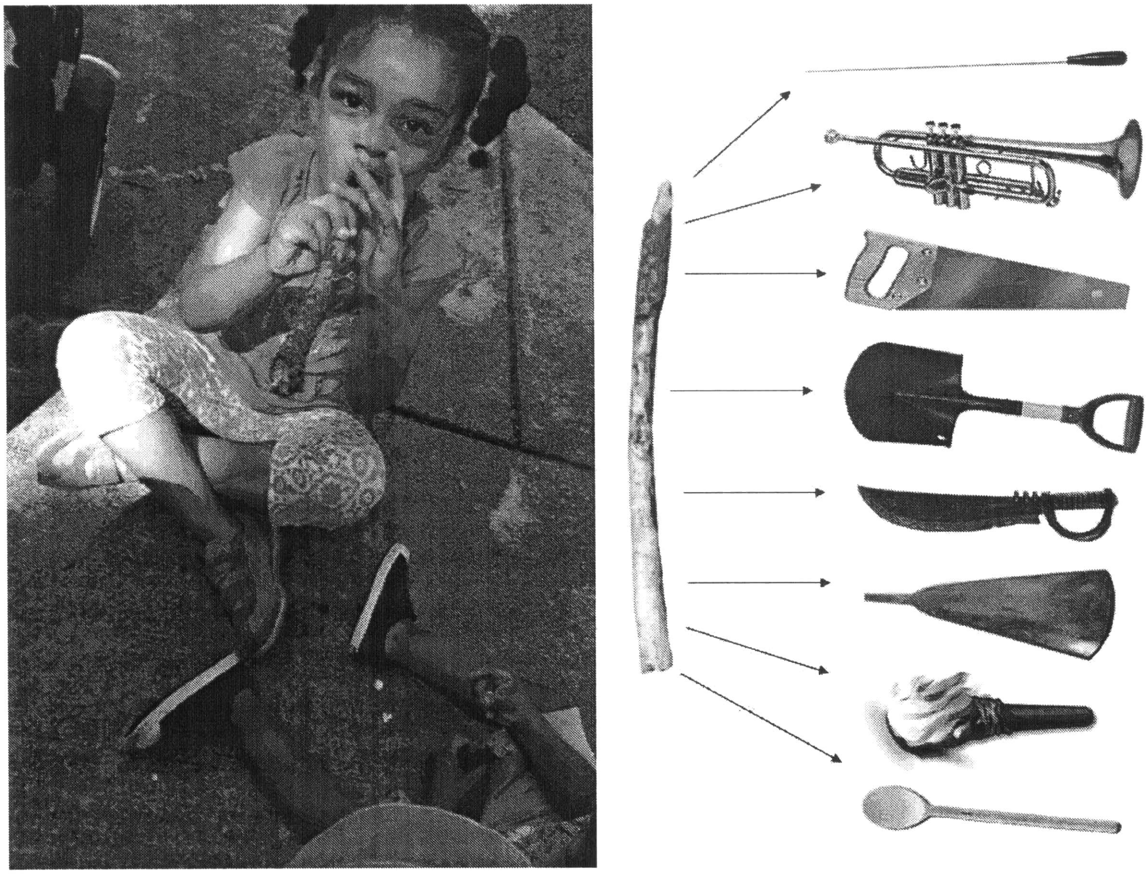

Figure 4.5: The different things a stick becomes during a child's imaginative play

Calculating with the eyes is not limited to playing with shapes that change because of what's embedded in them. This short example illustrates the power play has to allow individuals to use their eyes to assign and transfer meaning to what they see. In Taylor's case, the current assigned meaning often led to the next association, as in the case of the stick-trumpet becoming the stick-baton. Because she was in the play theme of "music," it was a natural switch of the eye and change of how she held the stick. The same was noticed in the stick-sword becoming the stick-oar as she entered into the play theme of "pirates." The sword and the oar were natural elements of that play world, and the stick became the instrument to take on meaning to enable that play.

Children in pretend play allow visual calculation to occur through the transformation of meaning of their surroundings and objects they hold (Ackermann, 1994). Objects and shapes can become anything that relates to their world of fantasy. This has also been referred to as "*meta-representation*" (Gardner, 1991). This form of calculation includes both the transformation of variables as well as the transformation of the empty set.

A child holding a banana up to her ear pretending it is a phone may be understood through the simple schema $x \rightarrow t(x)$. However, a child may pretend to drink tea from a play teacup that is empty. In this case, she is replacing the empty vessel with the imaginative content. Mime street performers are masters of this game. This is best understood using the schema $\rightarrow x$, in which the empty shape is replaced with the shape x. There is no limitation to this play, and it is completely driven by the world in which children create. Often, the actual objects and spaces are not reconstructed in the physical since, nor is there any type of visual overlay to the core object or space. Children completely reinterpret the object or space to fit their needs to enable their play.

Fostering this type of activity in children should not be taken for granted. As seen in the example above, it can happen completely on its own without any formal instruction. What impedes these moments of playful calculation usually are parents and teachers themselves, who often give children objects or activities that are not open-ended enough for children to do their meaning-transformations. If, for instance, you give a child an object, such as a specific doll from a specific narrative (film, book, or TV show), the child will likely stay within a singular strand of visual interpretation of that doll. That is to say, the doll will never become anything other than the doll itself. As a result of this type of pla,y parents purchase different discrete types of toys to foster each unique play activity the child wants to engage in. I am not championing an abandonment of popular off-the-shelf toys found in department stores. I am simply pointing out the limitations of play they might hold. The people who market them try to convince us of the opposite. It may be safe to say that a stick found in the park has more "features" to it than a plastic molded toy doll from Mattel or a Lego.

Children know this. The way they move through their toys with such boredom, always looking for the next, is indicative of the toy's inability to be flexibly interpreted. The stick does not need to be either a trumpet or a sword; it can be both and something new, depending on what children are playing at any moment. This is truly "flexible purposing"!

4.3 Toys and Puzzles

Toys prompt a particular type of open-ended play. There are many different types of toys, and each prompts a different category of play and a different mode of calculation. Any object can, in fact, be a toy. The design (or intent) of the object is not a predetermining factor to be a facilitator of play. Many of the toys we find today have their origins as objects that have been transformed and repurposed from being everyday objects, as is the case with the game of basketball deriving from an ordinary peach basket hung on a wall. The transformation of everyday objects for the repurposing of play is a faculty of visual calculation in itself and is the core of the design process for many toy makers.

Barry Kudrowitz and David Wallace (2010) describe a toy as a *"tangible item that is used for play."* They also agree that any object can serve the purpose as a toy, but they pay special attention to objects that have been designed with intention to perform the task of play facilitation. In their work, they designed a classification system to group and place all known toys as they relate to the way they are played with.

The "Play Pyramid" by Kudrowitz and Wallace (2010) contains four nodes representing the four categories of play that toys promote: sensory, fantasy, construction, and challenge. Toys that carry all four properties are placed in the center of the pyramid, those carrying three categories fall on the planes, those carrying two categories fall on the lines/edges, and those carrying only one category classification sit on the nodes. The Play Pyramid is a relatively new contribution to the study of play and games and has not been widely adopted by toy companies or manufacturers that typically adopt their own in-house system for toy classification. It does present, however, an effective method to organize the entire industry from the perspective of developmental psychology.

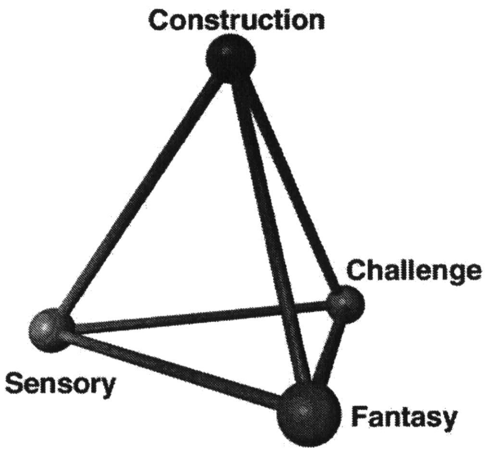

Figure 4.6: Kudrowitz and Wallace's Play Pyramid (2010)

From the standpoint of someone interested in calculation found in play, a different set of categories is useful. This taxonomy would need to place emphasis on the ways in which children calculate, whether visually, audibly, or beyond. In fact, Caillois's categories of play would work just as well (and perhaps better) to present the different intersections of play and calculation as they relate to toys. *Agôn, alea, mimicry,* and *ilinx* can take the place of each of the nodes and follow the same mechanics of the pyramid in placing toys on the nodes, lines, planes, and volume.

Puzzles are a unique category of toys that deserve specail attention. I call a puzzle a "toy" because it does embody a physical presence and faciliates play. However, we should note there are indeed puzzles that do not take physical form, as in the case of spoken riddles, jokes, and the like. The mechanical puzzle category of games has been heavily documented and most famously categorized by Angelo Louis Hoffmann(1893) in *Puzzles Old and New*. In this text, he describes close to 400 puzzles with their solutions. American historians, Slocum and Botermans(1986) have since expanded on Hoffmann's original text with their own research on puzzle games and provided their own classification of puzzle types.

1) *Put-Together Puzzles:* Putting the object together is the puzzle.
2) *Take-Apart Puzzles*: Opening or taking the object apart is the puzzle.
3) *Interlocking Puzzles*: Disassembly and assembly are required to solve the puzzle.
4) *Disentanglement Puzzles:* The puzzle is to disentangle and re-entangle parts of the puzzle.
5) *Sequential-Movement Puzzles*: The puzzle is to move parts of the object to a goal.
6) *Dexterity Puzzles*: Manual dexterity is required to solve the puzzle.
7) *Puzzle Vessels*: Drinking without spilling, or filling a vessel, is the puzzle.
8) *Vanish Puzzles*: The puzzle is to explain a vanished or changed image.
9) *Folding Puzzles*: The puzzle is to fold a paper, or a hinged object, to form a specified pattern.
10) *Impossible Puzzles:* The puzzle is to explain how an object was made or why it behaves in a seemingly impossible way.

For a full in-depth historical narrative for each category, these texts are great to read, but what you will not find is the emphasis on how visual calculation is at work in this category of play.

The stress of visual calculation at work in play activities will be made apparent in the following chapters. The game used in this study falls under the category of a puzzle toy type and overlaps with many of the categories outlined by Slocum and Botermans. Furthermore, it can also be understood as a shape grammar system following a set of rules that establish spatial relationships.

4.4 Games and Visual Calculation: Precedent Studies (Contemporary Examples)

In the following section, I would like to briefly look at a few contemporary examples of toys and games that indirectly pull out visual calculation skills as core components of game play. *Lego* is the most obvious toy that jumps out when thinking about "computational toys," but as I will show, they do not offer much in the type of visual calculation I want to consider. In truth, *Lego* (originating in 1949) offers nothing new to the computational model of play that had not already been discovered by the locking block toys of the Bauhaus (further developed by Kurt Naef[24]) or *Lincoln Logs* (1916). I would also like to add that these studies present only a small segment of what has now come to be known as "thinking toys."

4.4.1 Sorting Games

There are several types of games that can be classified as sorting games, requiring the player to either decipher matches among pairs or place items in a specific sequence. These games often carry the same characteristics of puzzles but have added game mechanics such as time constraints or opponents to transform them into "game" play activities. For instance, the game *Tetris* is the gamification of a puzzle-sorting activity similar to *Tangrams*. As soon as I place this system with the added components of time constraint, the randomization of pieces presented to the player and defined win/lose conditions, the puzzle activity is now a sorting game.

---

[24] Büren, C. Von, & Clahsen, P. (2006). *Kurt Naef: Der spielzeugmacher.* Basel, Switzerland: Birkhäuser, for Architecture.

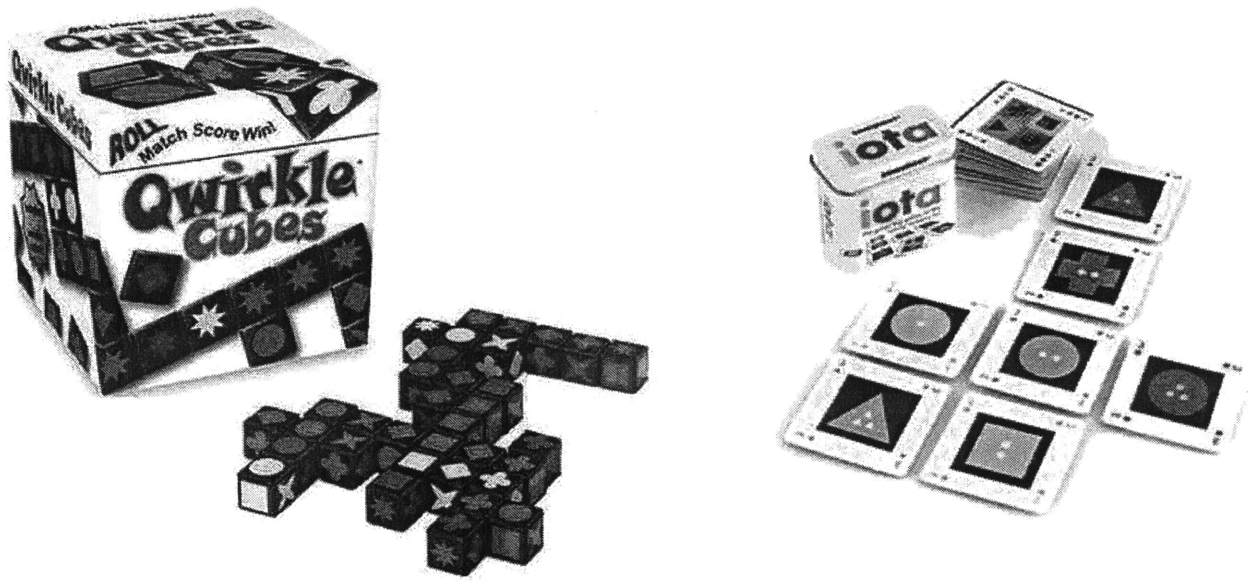

Figure 4.7: Examples of sorting games—Qwirkle Cubes *and* Iota

Sorting is a very common game mechanic found in many tabletop games. Most card games are based on/around sorting; in fact, when players get a dealt hand, sorting is the very first activity most of them do! All combinatorial system-based games are not the same though. Some are much more generous than others in how they enable the player to have multiple approaches to the solution. For instance, the games *Qwirkle* and *Scrabble* are essentially the same type of sorting game. For *Scrabble,* the players place the tiles following the pattern of the proper spelling of words they come up with. For *Qwirkle,* letters are replaced with rules that determine how tiles are placed with either matching colors or shapes. *Iota* and *Set* are two other popular games that follow this same visual matching game with a combinatorial tile system.

I have developed a classification of these play systems based on two factors. *First, how dynamic or fixed is the playable solution (Figure 4.13)?* For instance, games like *Scrabble* and *Qwirkle* are very dynamic in the playable solutions during game play. The board is constantly changing; therefore, the players are constantly adapting to the situation to play the best solution based on the tiles in their hands. Alternatively, the game *Q-bitz* works like a jigsaw puzzle in that the targeted solution is fixed. There is no dynamic change on the possible moves one can take, in that there is only one correct playable solution to win.

Figure 4.8: Q-bitz, a game that works like a jigsaw puzzle with no dynamic change

Secondly, I ask if the player is trying to achieve a win state? In playing with *Tangrams* or *Legos,* there is no specific win state; however, the game *Shape by Shape* by Think Fun has added the necessary element to *Tangrams* to make it into a game. The player is no longer in open-ended inquiry but is now trying to achieve the specified composition in a set amount of time. Jigsaw puzzles offer somewhat of a paradox because, although the player is not racing against the clock, there is a desired win state achieved in completing the puzzle to reveal the full picture. For better or worse, *Lego* has also taken on this approach in presenting many of its newer products as kits with very prescriptive steps for the child to achieve a singular correct configuration.

Figure 4.9: Shape by Shape, an example of games where players are trying to achieve a win state

The games *Izzi* and *Cirplexed* are both play examples that have high dynamics and, at the same time, do not try to achieve win states. Players take turns putting down tiles with simple rules that dictate what they can do based on the configuration on the table. The game ends once players are all out of tiles. In this way, the game is very open-ended, and the play supports visual inquiry; on the other hand, there is no time element or opponent to achieve a win state. Because the players' actions are bound by a set of rules, these games move us a step closer to game play than *Lego* and *Tangrams.*

Figure 4.10: Izzi and *Cirplexed,* high dynamic games that do not try to achieve win states

While it is true that any game can be appropriated to be played with in any way the players see fit (house rules), the following graph attempts to layout my system of classification to place puzzle, toys, and games under classification.

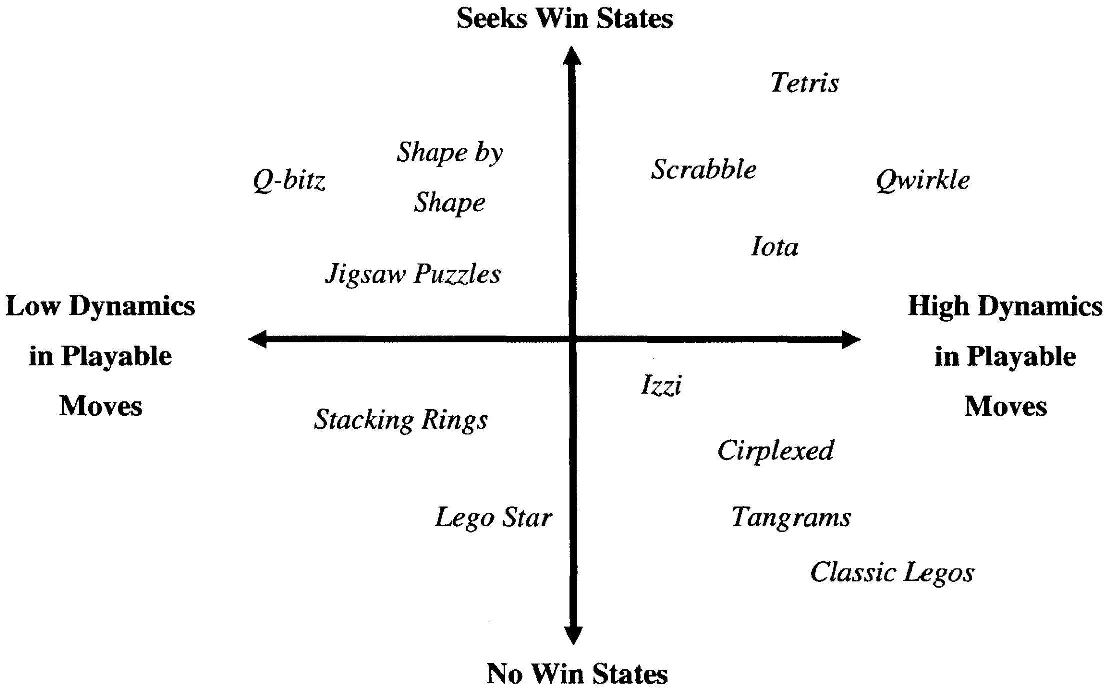

Figure 4.11: Graph of the author's system of classification for puzzle, toys, and games

4.4.2 On the Dot (Game Analysis)

On the Dot may be considered a game of sorting, but its mechanics and game play set it apart from most others of this category. *On the Dot* is a tabletop card game developed by *Brainwright Games*, a subsidiary of Game Wright Games and Ceaco, Inc. Their philosophy and mantra for game design is to make products for "curious minds." The game is classified as a "brainteaser" and is marketed for players age 10 and older. It can be played individually, but can also be played competitively with up to four players. As such, it presents the player with a definitive desire to reach a win state, but the playable moves are much more dynamic than the typical sort and match puzzler.

On the Dot is played with four transparent cards, each with its own unique pattern of colored dots on it. Players have their own set of four pattern cards demarcated by a specific rim color (red, purple, green, or yellow). The second component of the game is a deck of 64 pattern cards of colored dots similar to those seen on the transparent pattern cards. The game is played with one of the 64 pattern cards being revealed and the players then racing to stack their transparent pattern cards so that the composition of dots match the pattern card. Players must have all of their cards stacked so that the pattern revealed on top is an exact match to the pattern card below it. Although the dots on the card are fixed, the rotation and flip of the card, along with its stacking order, allow dots to move around and embed within each other to reveal the master pattern on top.

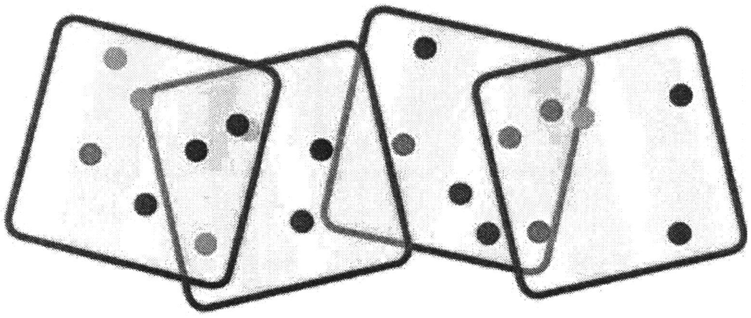

Figure 4.12: On the Dot, a brainteaser game

One model for understanding this game through shape grammars can be seen using the schema $x \rightarrow x + t(x)$. At first glance, a player may not understand each of the cards as being identical, but we have to understand the shapes by two different qualities, the location of the nodes and the color of the nodes. If we ignore color temporarily, we can see that each card has four points that are placed in the exact same location. Transformations of copied cards for this game are restricted to 90 degree rotations and a reflection transformation that flips the card. Since solutions are formed by all the cards stacking on each other, the game is restricted to translational moves on the Z axis. Identifiably reflection, rotation, and translation (restricted to the Z axis) constitute the entire schema of possible moves.

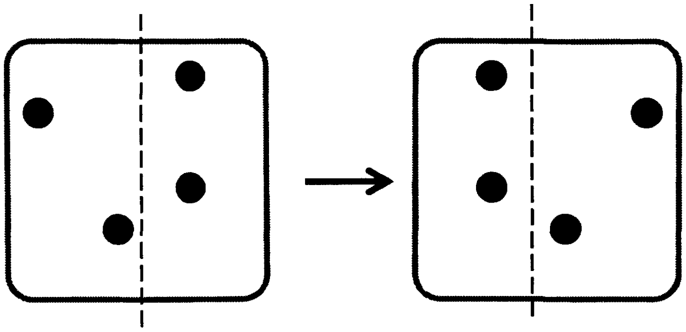

Figure 4.13: Playing card transformed under the schema x → t(x)

The rule above shows the schema x → t(x) in which the card is reflected.

We can use the schema x → x + t(x) to demonstrate when the card is copied and then reflected and placed on top of the base card.

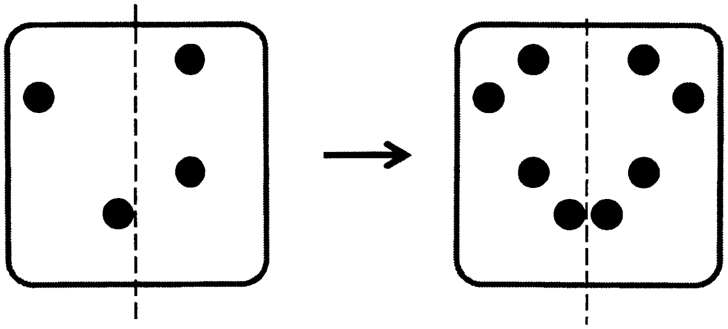

Figure 4.14: Playing card transformed under the schema x → x + t(x)

The location of the points may seem arbitrary, but we can further understand these locations by considering all of the possible locations of a point in the shape. This can be seen by locating all of the point locations in each of the card transformations. Once this is done, we reveal an underlining pattern in which there are four groups of points in which each group has a collection of four points. Depending upon the orientation of the card, points can inhabit any one of these sixteen positions. When cards are stacked, more nodes take on filled assignments.

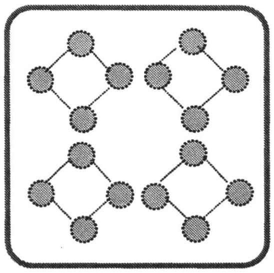

Figure 4.15: An example of stacked cards where more nodes take on filled assignments

Another type of transformation occurs with *On the Dot* in that, with each of the cards, there is a translation of the color of each point on each card. Each card is identical when lookng at the dot placement, however they are not identical in the assigned color of the dots. To achieve variety in color assignments the cards use a reflection rule swaping colors from one side of the axis to the other. The example below shows the reflection of colors as they are assigned to the space on the card. This is a different type of reflection.

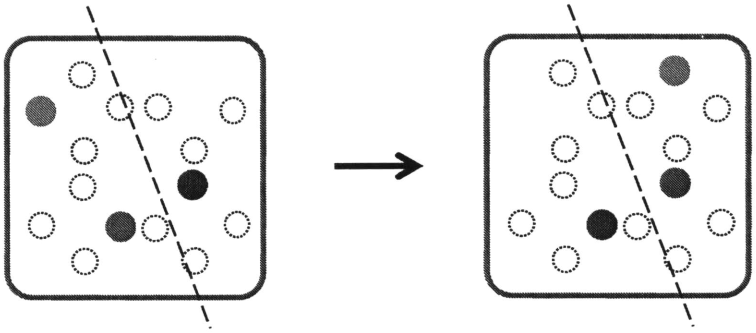

Figure 4.16: Playing card transformed by color weight assignment

This game can quickly get complex as players are constantly considering both the location and the color of the nodes as they perform transformations on the cards. Translating along the Z axis allows players to sometimes embed the color dots into each other, thus allowing players to hide a dot, a necessary strategy for some of the puzzle's solutions. Once we begin to analyze the game's mechanics through shape grammars, we can easily see how this is about playful calculation.

4.4.3 Pix Mix (Game Analysis)

Pix Mix by Mindware is not a game of sorting, but rather a game of unraveling. In the same way disentanglement puzzles require the player to pull things apart, this game prompts the player to pull the composition apart visually. Similar to *On the Dot,* the game is played with transparent cards, but this is not a game of logic or spatial geometry. It is a game of visual dexterity.

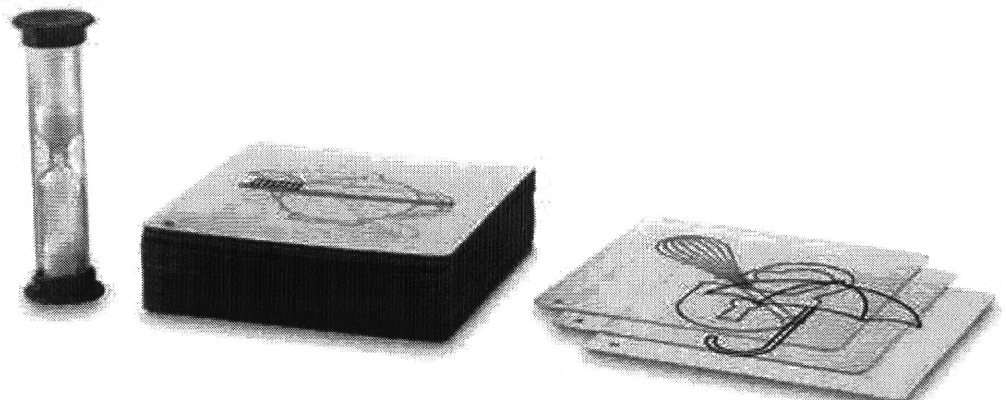

Figure 4.17: Pix Mix, a game of visual dexterity

To play, players take six transparent cards from a deck of 80 and stack them on each other without looking at their hands. Each of the cards has a unique line-drawn picture on it of everyday objects (a telephone, football, bowling pin, and lamp to name a few). Once they have the cards stacked, they start the timer and look at their hands (all stacked together), trying to decipher what they see. Because the cards are transparent, the lines of each of the cards begin to embed within each other into one jumbled composition of interlocking lines. As they discover each hidden object, they write it down on a small sheet of paper, listing as many things as they see before the time runs out. The player with the "best eyes" or who has the most found the most objects wins that round of game play.

Figure 4.18: Stacked transparent cards

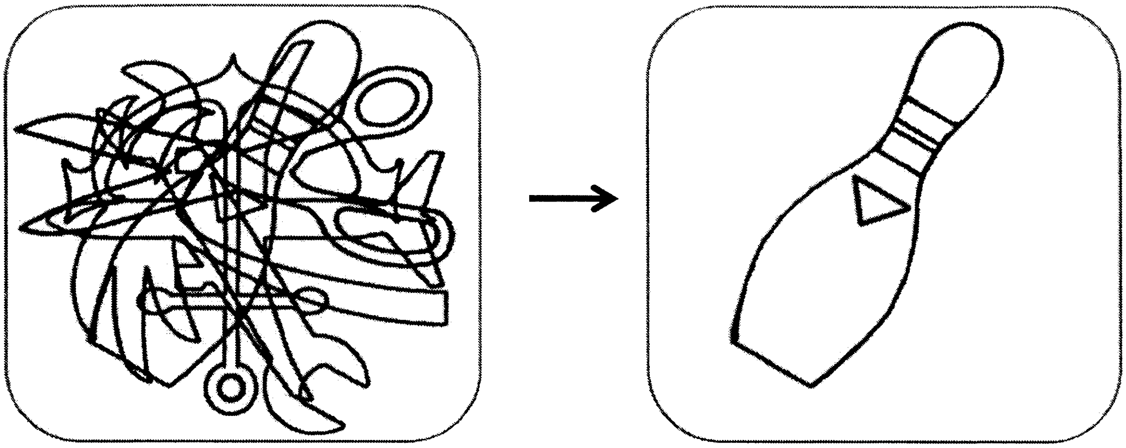

Figure 4.19: A bowling pin, an example of seeing something others may not see

The schema x → prt(x) is a great starting place to understand the shape grammar mechanics found in this game. Rules that follow this schema allow players to select a part of the base shape, and that is exactly what is happening with their eyes. Players are seeing what they want to see and pulling out things they understand. Of course, there is more than meets the eye than the collection of compositions represented on each of the individual cards, and this is where *Pix Mix* comes up short. Although the activity of finding the embedded shapes of everyday things is a fun activity, I also want to get points for the things I see NOT listed on the list. The example above was made with cards that had an anchor, palm tree, wrench, scissors, airplane, and bowling pin (see if you can spot them all). But this leaves out the other things that I may see.

In fact, I may see a fanged were-wolf staring back as I look through this jumbled collage of lines. *Pix Mix* does not allow for this, but in expanding on the rules and playing the game this way, I can take any part I want with my eyes and remove the parts I don't need. This is the playful calculation that I want to talk about. It's that type of calculation that is generous, non-combinatorial, emergent, and playful. This type of calculation serves whatever I need.

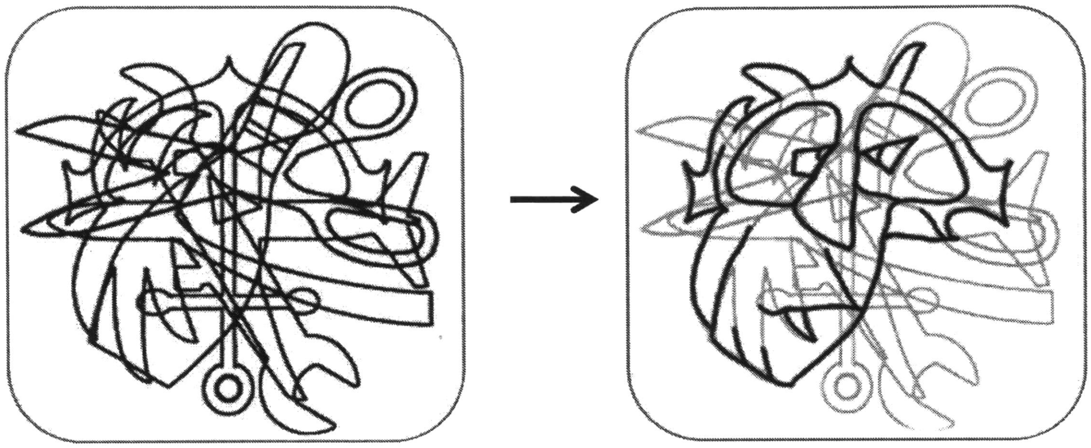

Figure 4.20: A werewolf mask, an example of seeing something others may not see

4.5 Games to Teach Design

The games I will describe in Part Two of this thesis were designed with the intent, to bring the players into a deeper level of play that extends beyond entertainment. Through these games, players can enter into the same modes of thought that good designers inhabit. The uniqueness of these games in study is that they accomplish "design thinking" through the usage of rules and algorithmic thinking. The players approach creative thought through playing with rule systems based on formal logic. At the same time, the games themselves maintain their base level of enjoyment. This is the core feature of playful calculation.

Ideally, the games described in Part Two of this thesis can serve as teaching manipulatives to introduce players to the entire enterprise of shape grammars and designing with rules. Through playing with these games, the player learns about visual calculation through the process of playful engagement. This is a complete constructivist approach to teaching students this alternative design approach. Additionally, this study will present design in a very approachable manner to those who do not feel they are the "creative type." Anyone can be creative, and the games in this study have proven to show some truth in this statement.

In these games, we find the basis for a broader understanding of design thinking and the creative process. A research focus on *Playful Calculation* introduces students to the inherent relationship between creative thinking and ludic modalities. We can use "critical games" to analyze organizational behavior and decision making among groups. Games and game play can also be used to explore lateral thinking, collaboration, and innovative decision making.

Play brings to surface myths we hold on the separation of work and play; furthermore, it gives managers another tool in their tool-belt to better understand latent problems in their organization. This concentration will equip future leaders on how to use play strategies to create healthy work environments and bring inspiration to the workplace.

Finally, we see in this game a building on the core concepts of *computational thinking*. The games used in this research are computational in nature and lend themselves to prompt designers to approach their work in new ways. Computational thinking does not replace commonly held notions of design thinking but encompasses it, expanding the subject to formal systems of logic and rules. In an era of big data, it is important to have the skills to think in systems. How do we solve problems through the creation of algorithms that yield multiple variations to a solution rather than a linear model? This area of concentration answers these questions and more as we learn to be more mindful in the way we use our technology.

At the foundation of this research on play, I place shape grammars. Shape grammars are perfect to facilitate all of these things in the design process because they allow the designer to embrace the play forms of *ilinx* and *alea* while providing formal descriptions of these wild and crazy activities. Games and play are ambiguous, and this ambiguity is good. Shape grammars bring rigor to these ambiguous ways and leave a door open for design flexibility. Shape grammars do not lock the designer into one way of playing, but as I will show in the next section, they allow the designer to constantly expand the magic circle.

Part Two

Chapter 5

Shape Game Study (Task Description)

The game created for this research, called the "*Shape Game,* " has a series of phases (or mini-games) that a player plays through. Each phase of activity is played with a set of identical transparent shape game pieces outlined in black. The shape itself is a non-symmetrical hexagon approximately 5" x 5". For set up, pieces were scattered on a large light table in the Children's Museum's common space. In addition to the light table, small colored game tables were used periodically for the study.

These games can be played individually or in groups. Through observing the game play, I saw how students deal with geometric transformations and rules as a procedure to create 2D art compositions. This game also attempts to teach concepts of embedding and recursion as a technique for creating art. As a result, it is expected that algorithmic thinking will be strengthened as players play this game and are forced to make sense of visually abstract systems.

5.1 Research Methods (Creating the Game)

The process of creating a game is very similar to any other design-based research endeavor. The experimentation conducted in creating the game gives as much to the body of research as does the observations of players playing the game. To design a game, the researcher is engaged in the exact type of reflection in action as described by Schön. This research begins with the same type of "What if?" question that most research is based on. The process begins by creating early prototypes, followed by testing through play, and then goes through refinement. It sounds a lot like what architecture and design students go through; however, there is much more. After the games were refined, I recorded observations of game play to inform both the existing game as well as the larger concepts of design and creativity.

The learning sciences have done much in promoting design-based research methods. Game-based design research is a natural evolution to this pedagogical approach to create new knowledge. The use of games allows designers to observe interactions of the research subjects while, at the same time, they are responsible for creating the environment in which the subjects are being studied. Games as systems are inclusive of the environment in which they are played.

Salen and Zimmerman (2003) speak about the various ways we can understand any play system as being understood *formally, culturally,* and *experientially.* The *formal* qualities of a play system include the rules of the game as well as the physical components that make up the game (objects, players, space). The *cultural* lens to understand a game considers the way the game interacts with the other circumstances of the players, including societal positioning, language, historical context, and sometimes even regional location. Finally, a researcher could look at the *experimental* qualities of a play system. Here, we take into consideration the players and the strategies they use to play the game (there are also emotional and social components that are attached to experimental qualities of a game system).

Considering these various ways to frame a play system in using it for design-based research, this work focuses on the *formal* and *experimental* qualities attached to the game created for this study. As I hope to show, it is in these two domains that we begin to have a deeper understanding for how visual calculation works naturally when people are in a state of play. Furthermore, the formal aspects of the game (materials and mechanics) allow players to learn design in a way that is both computational and playful.

5.2 Early Prototypes

A series of pilot studies were conducted to establish the shape of the final game piece. In these early studies, I went through an interactive process, testing out several shape pieces and observing the affordances they offered when I and others played with them. Things I looked for in the ideal piece included:

1) A balance between conventionality and irregularity in the base shape
2) Ability for a shape to produce non self-repeating shapes as it is used in composition with transformed copies of itself
3) Ability for a shape to disappear to the eyes as it gets embedded with transformed copies of itself

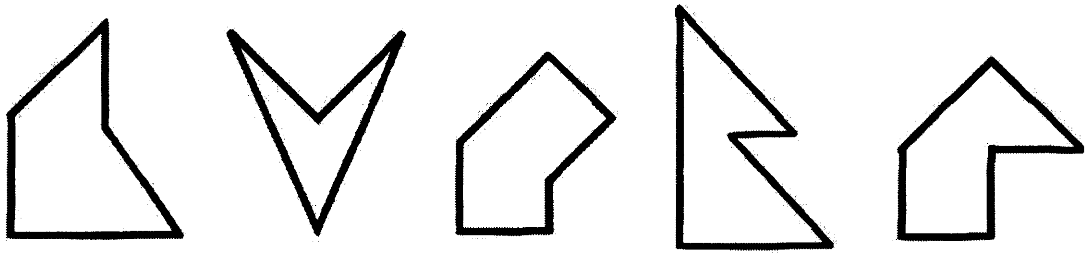

Figure 5.1: Shapes of early prototypes for game

All of the prototypes were shapes printed out on 6" x 4" transparent paper cards. One idea was to present all of these trial shapes as a set very reminiscent of a Froebel gift. The players would receive a deck of the transparent cards and then make compositions with each deck of shapes. This seemed too similar to the Froebel gift 7 (shape tiles) and also lost some appeal when players began to mix the shapes, losing the magic of finding the undescribed new shapes from playing with the copied pieces of just one shape type.

The early prototypes of the game had unique dynamics and scripted methods of play that led to the final design and implementation of the *Shape Game*. In these studies, the shapes and games played with them were separated into three unique phases. Each phase was designed as group play activities in which collectively the players create a composition. The composition was complete when players decided to use their turn to stop play or when they exhausted their shape cards.

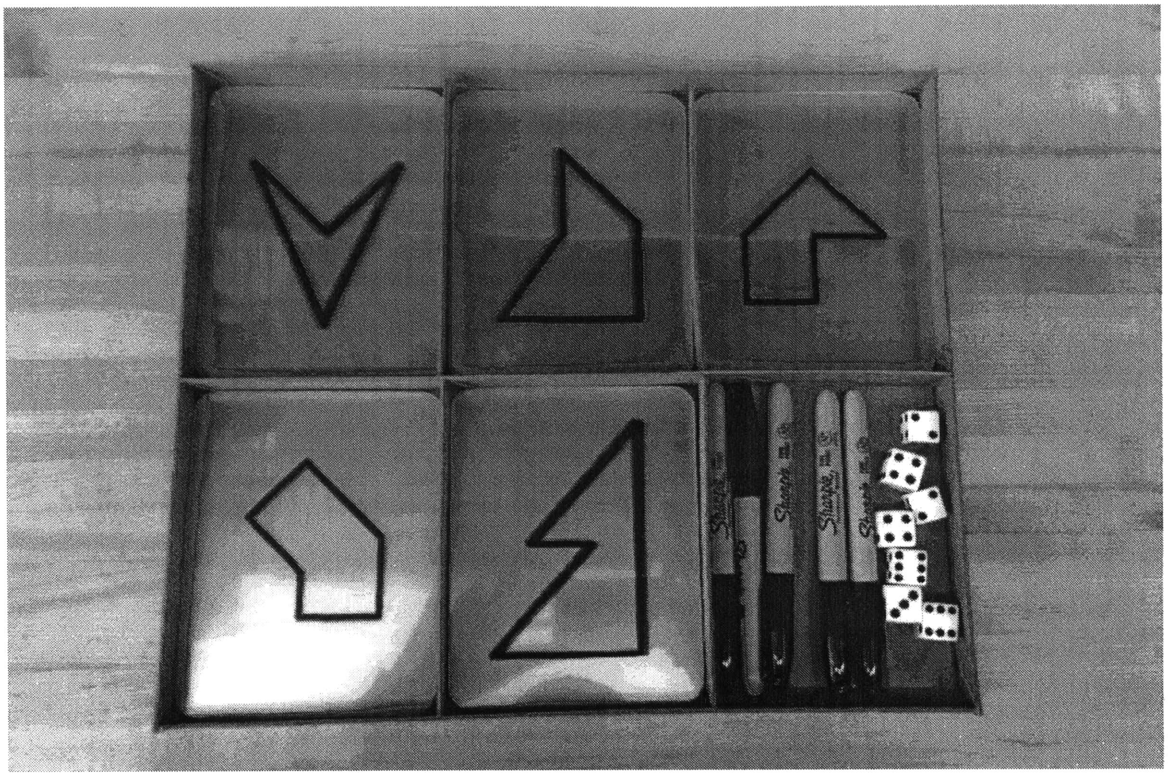

Figure 5.2: Early prototype of the *Shape Game*

5.2.1 Phase 1: Free Play

The first iteration of playing the *Shape Game* is a game with few limitation. First, a base shape is placed on the table. Each player then takes a turn to add a copy of that shape to the table, thus creating a design. Players can place their shapes anywhere on the table, deciding which geometric transformation they will apply. Collectively, the players create a composition. The composition is complete when another player decides to use his turn to stop play or when he has exhausted his shape cards.

5.2.2 Phase 2: Kit of Action

Phase 2 of game play introduces new game mechanics and components. While the game play of Phase 1 allows players to take moves sequentially without any restrictions, Phase 2 introduces forced actions by chance through the use of cast dice. Before players take their turns, they role a die to determine the actions they are restricted to in play (see Figure 5.3). While rolling numbers one to four allows players to use the same geometric transformations they used in Phase 1, rolling a five or six ads to the possible actions of play. When players role a five, they can use a blank shape card and a marker to "trace out" any new shape they see embedded in the composition. There are no limitations to that new shape other than it must fit on the blank trace card. Once players have drawn out the new shape, they are free to apply a geometric transformation and place it on the table. To complete this phase of game play, there is also the consequence of rolling the unlucky six in which players lose their turn.

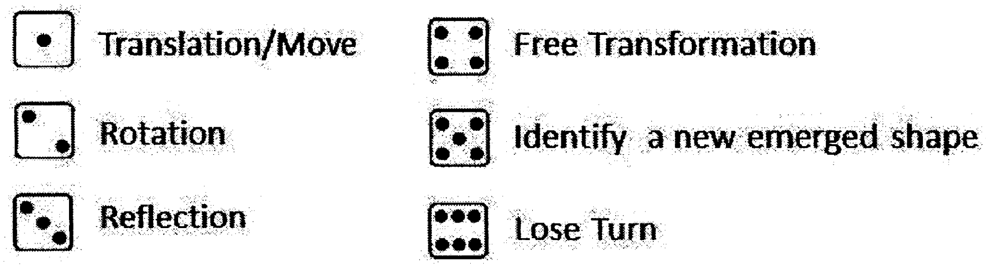

Figure 5.3: The consequences for a roll of the die

5.2.3 Phase 3: Play Your Rule

The third iteration of playing with the "shape gifts" is a game that introduces spatial relationships as design rules. A base shape is placed on the table. Players create their own composition of a spatial relationship between two copies of that base shape. Players take turns to add to the base shape by playing shape cards only in the same fashion of their design rule. Players can embed their shape anywhere on the table as long as they are keeping to their design rule.

Although many of the components of these first studies were abandoned or transformed completely, they did inform the final design in ways that could not have been accomplished without this iterative process.

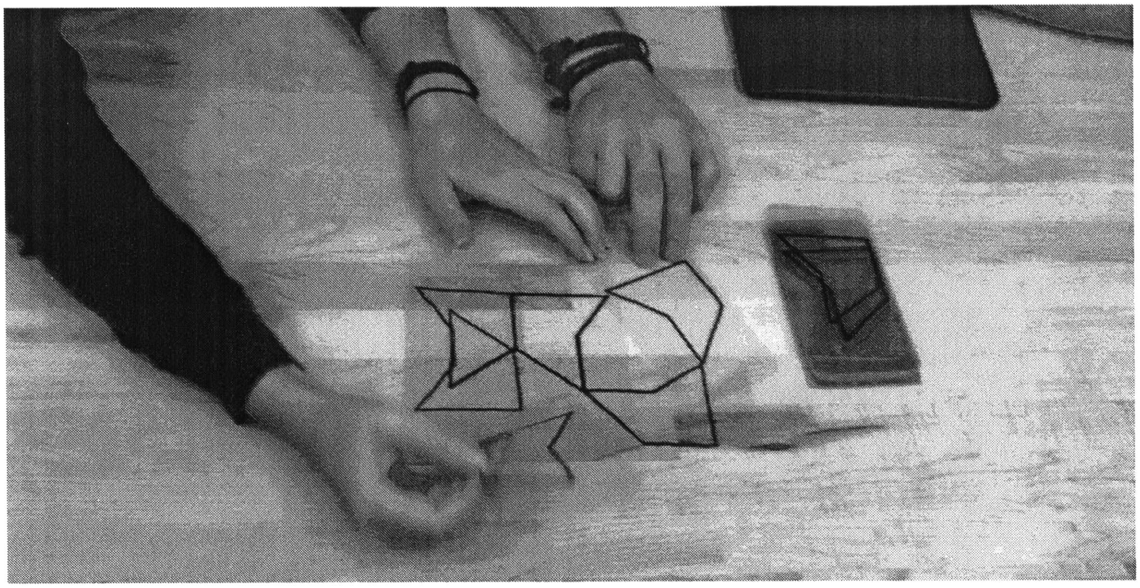

Figure 5.4: Players adding their own shape cards to those on the tabletop

5.3 Analysis of Game Pieces

The shape, a non-symmetrical hexagon, was decided on for the final game piece because of its wide range of ambiguity and abstraction. In its "DNA," this shape contains the basic geometries of triangle, square, and rectangle. This shape is none of these by itself, but rather produces the basic shapes through the combination of two or more game pieces. The schema x → div (x) and x → prt (x) can be used to understand the different ways of seeing this relationship the non-symmetrical hexagon has with the basic geometries. First, we begin with a basic square and start to divide it in half. Secondly, we go about dividing it diagonally at 45 degrees from corner to corner. Finally, we can pull from the composition a single part, which is how I understand this non-symmetrical hexagon (Figure 5.5).

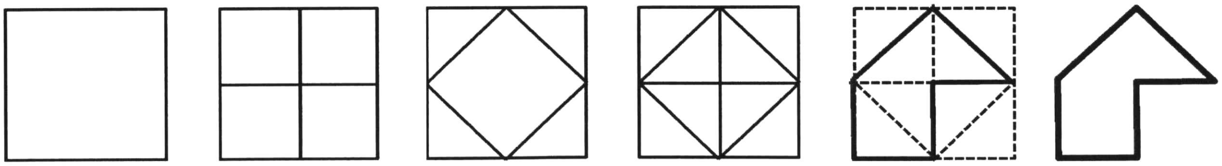

Figure 5.5: The relationship the non-symmetrical hexagon has with the basic geometries

In playing with this base shape (because of its relationship to the triangle and the square), basic geometries are naturally emerging shapes when you begin to combine the shape pieces together. I wanted to allow children to play indirectly with these primary geometries through shape emergence. Players can overlap and place shape game pieces on each other, allowing the lines and edges to fuse together. The transparency and thinness of the game pieces allowed the players to work with the game pieces as is if the lines were on one surface. This enabled players to discover both embedding and the emergence of new shapes as they interacted with the game pieces.

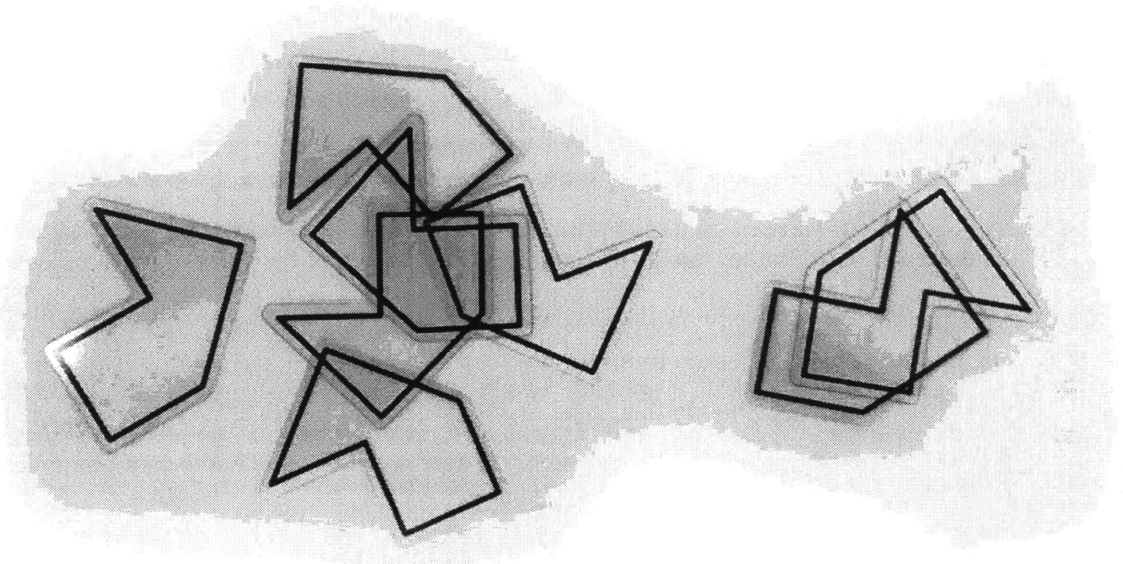

Figure 5.6: Plastic, transparent shape pieces

Another interesting component of this chosen shape is the presence of what I call invisible connector nodes. There are an infinite number of points that lie along the lines of this shape, but there seem to be major and minor location points along them. The most noted points would be the ones that make up the boundaries of each of the lines. Remembering that this shape is two dimensional, we can make note that points are the boundary of lines, and lines are the boundaries of planes and various other 2D shapes, as is the case in this non-symmetrical hexagon shape.

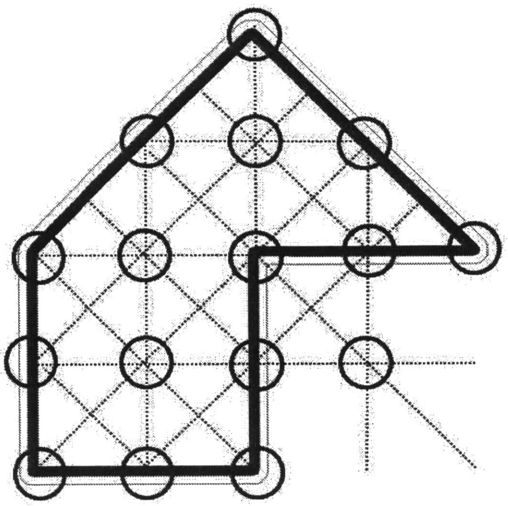

Figure 5.7: Invisible connector nodes of a shape made visible

The second tier of nodes makes up the midpoints of each of the sides of the six sides of the shape. Once these vertices are established, we see the creation of new line segments that intersect the shape and, therefore, can produce new vertices at the midpoints of these new lines. If we continue playing this game of subdivision and vertices identification, we find ourselves back at the beginning statement, "There are an infinite number of points in and around this shape." However, these boundary points and invisible connector nodes do show up naturally when players begin making compositions with the base shape in unnatural ways. Perhaps due to the player's intent, trying to make sense of the shape and seeing how it relates with copies of itself, we see these natural places of intersection.

Another surprising feature of this shape is how it produces self-repeating shapes of its own kind in certain compositions. For instance, the shape has the ability to create itself using the inverse boundary of its sides. Consider the composition using the schema $x \rightarrow x + t(x)$ with the following two rules.

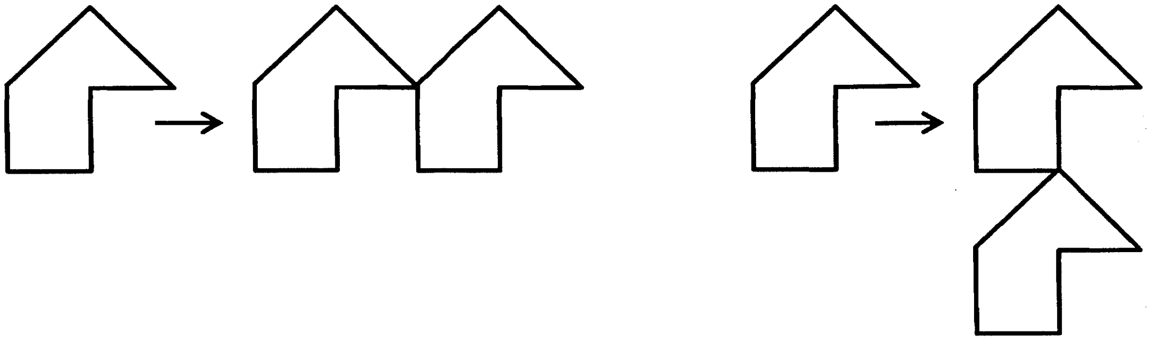

Figure 5.8: Two self-repeating rules of a shape

When these rules are applied, we find a fifth shape emerges that is reflected and rotated 180 degrees.

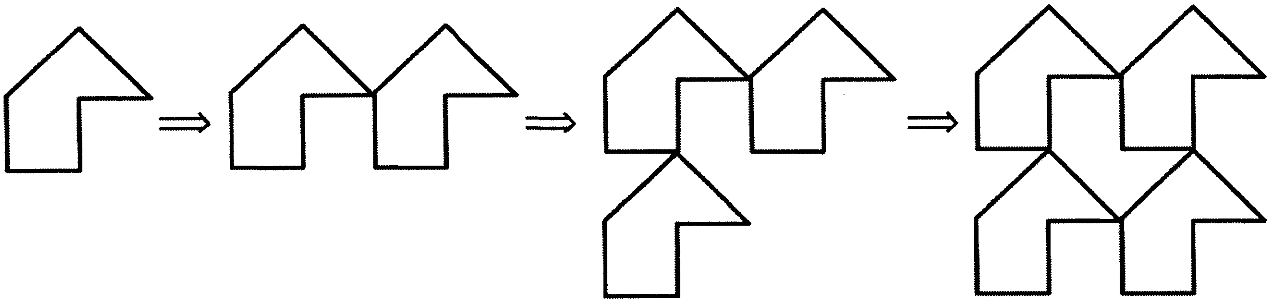

Figure 5.9: The emerging shape

This is what happens with visual calculation! Our eyes are able to detect more than combinatorial systems would dictate. Shape reoccurrence also occurs in producing the same shape at different scales.

Consider another composition using the schema x → x + t(x) with the following one rotational rule.

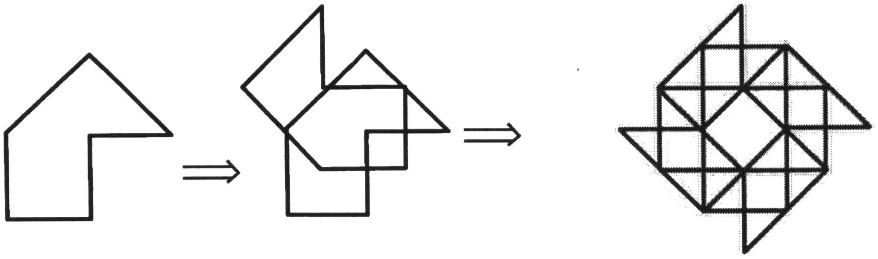

Figure 5.10: A composition using one rotational rule

In this composition, we find the non-symmetrical hexagon base shape at a variety of scales. The first copies we find appear to make the following rotational composition:

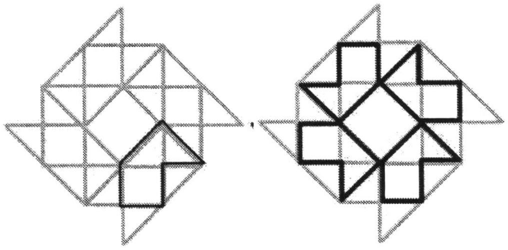

Figure 5.11: The rotational composition of the first copies

And in looking again, we find the shape at another scale with two other compositions.

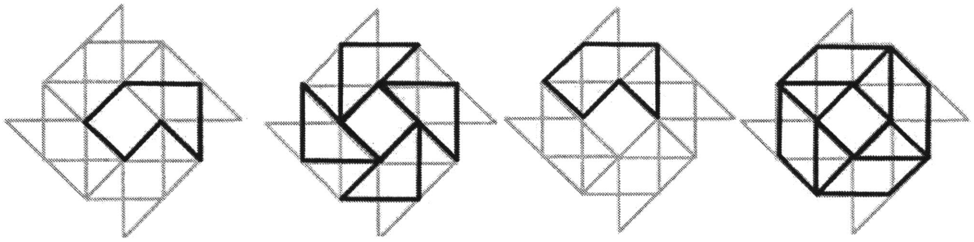

Figure 5.12: Two other compositions of the shape

Identifying these scaled-down copies is a fun game to play with the eye! Upon identifying them, we see they begin to carry out a unique set of rules to make beautiful compositions on their own.

Finding hidden shapes embedded in the game is not as straight forward as it may seem. Take, for instance, the task of generating a square from the base non-symmetrical hexagon shape. First, we have to copy the shape with a rule based on the schema $x \rightarrow x + t(x)$, but what transformation do we perform to find our square?

The first approach may be to see how much of a square I have before I even go about copying the shape. Upon quick inspection, I may be drawn to the three lines that make up the edges of the lower half of the shape.

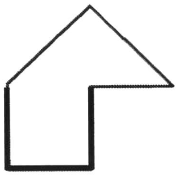

Figure 5:13: The "U" shape

It's a "U" shape that is almost a square, but I see it is missing a line that would make the top edge between the two end points of the open shape.

If I perform the translational rule,

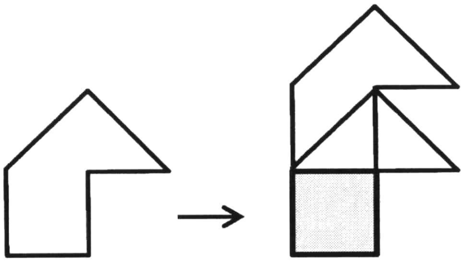

Figure 5:14: The shape after the transformational rule is applied

that would work nicely because the translated position of the copied shape has given me the line I was looking for to complete my square. In reality, any of the edges of the copied shape could serve as the missing line I was looking for. We could create the following rule to get our square:

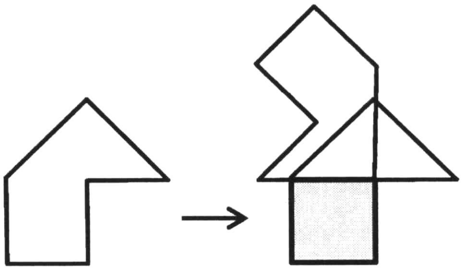

Figure 5:15: The rule used to get a square

Since there are six sides to the copied shape, each having four different transformations to it, we can find 24 different solutions to finding our square using this approach.

Perhaps, we are not interested in making squares out of the "U" shape embedded in the irregular hexagon. What can I do if I am drawn to the lines forming 90-degree angles, the corner shapes?

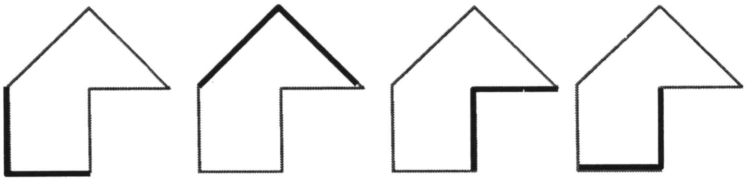

Figure 5.16: The four "L" shapes

We see that there are four of these "L" shapes to play with, which may make a much more generous starting point for me to generate my square. Once again, we will have to make a copy of the base shape and transform it to get the other portion of my square. We can do this easily with a rotational transformation rule.

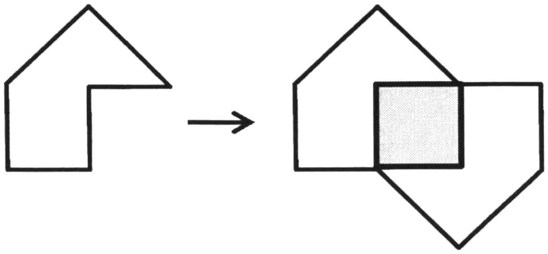

Figure 5.17: Adding a rotational transformation rule to the "L" shapes

It is easy to see because I am using the same embedded "L" shape from each of the non-symmetrical hexagon shapes to get both halves of the square I am trying to make.

Again, I am not constrained to use the same referenced embedded shape in the copied shape. In fact, I could use any of the four "L" shapes I originally identified to create a variety of rules, each giving me the square I was looking for.

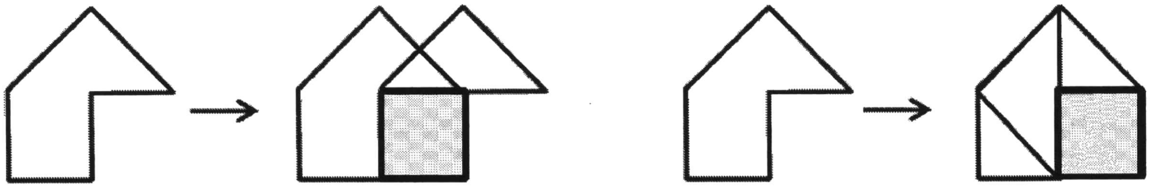

Figure 5.18: Different rules used to get the desired shape

Figure 5.19: Rules used to get squares

The last rule picture above is of particular interest because it gives me three squares! When we begin performing these types of calculations, we can find 64 different approaches using these base strategies, an infinite number of squares as I watch them grow and shrink by adjusting the rules parametrically.

In the world of design, the operator would not be constrained to copy the entire shape to perform any of these tasks. If I wanted to take a portion of the shape I thought I needed to make my square, I would simply write a rule under the schema x → x + t(prt (x)). That is like making a copy of just the piece I need and transforming it to a new positon. The *Shape Game* does not allow for this type of action (unless we go about cutting up the game pieces), but it does allow for a rich game of embedding and shape emergence.

The *Shape Game* is very effective in presenting the system of shape grammars and visual calculation. The way the game pulls the players into a way of seeing the new shapes and prompts them to forget the base shape is exactly what shape grammars are all about! In this type of calculation, you do not hold onto the identity of the starting variables; you are allowed to forget them and calculate with new emerged shapes. Take, for instance, the following composition shown in Figure 5.20:

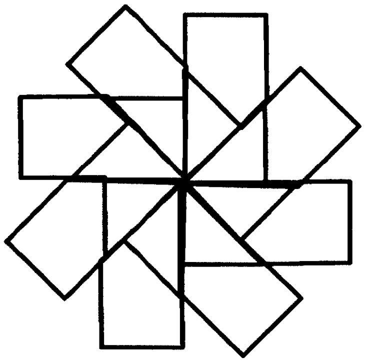

Figure 5.20: A composition of rectangles

I happen to know that is was created by using eight of the non-symmetrical hexagons all rotated around a shared point. However, this is not as important as what I look at. After looking at it for some time I no longer see the base shape but see a composition of rectangles. Figure 5.21 shows this duality of interpretation. With this type of calculation I do not have to choose “either-or,” the composition can be “both- and.” This type of seeing and calculating is what the *Shape Game* enables and is what visual calculation is all about. It allows us to pull from compositions a formal way of explaining it, using a system based on what my eyes see.

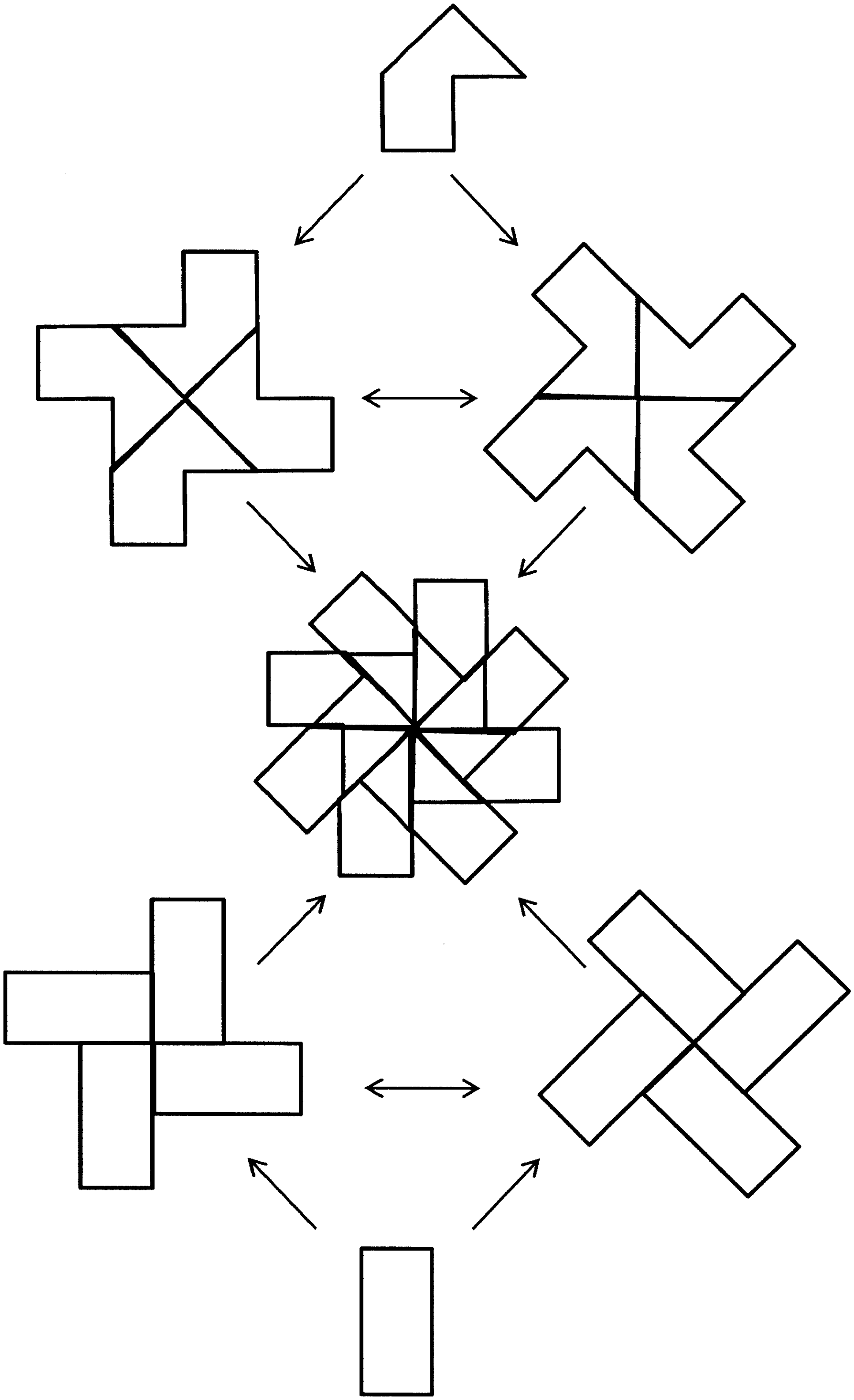

Figure 5.21: A duality of interpretation

5.4 Game Phases of Play

Similar to the pilot study of game play, the *Shape Game* was conducted with several phases of game play. Each phase scaffolds the learning experience, building on the previous phase of play. While there were no initial limitations placed on who could play each of the phases, I did find that the age and development of the players did contribute to the success of each of these ways of playing with the shape cards.

5.4.1 Game Phase 1: Free Play

The first iteration of playing the *Shape Game* is a game with few limitation. Players take as many shape pieces as they like and play with them however they like. At times children took the pieces and slid them all over the light table, seemingly delighted by how lines fused together in a big jumbled mess. The younger children were often the most enthusiastic to just slide and jumble pieces around. It was as if they were playing with a giant kaleidoscope. For younger children, the kinesthetic and tactile are just as important as the visual qualities of the game pieces.

A game of symbolism was the second type of activity children did during free play. From our documented observations, one configuration continued to emerge as a source of amusement, the house (Figure 5.22). The most common operation to achieve this was the reflection of one game piece partially embedded on another.

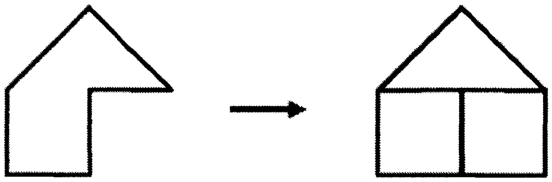

Figure 5.22: The "house" shape rule

While the house composition was prominent as the most verbally articulated design discovery, there were several other congigurations that did come up when children were in free play, including: bats, ducks, crowns, and even a "Star Wars TIE Fighter" spaceship. You can use your imagination to compose these designs for yourself! Play is often either a competition for something or an imitation of something (Huizinga, 1950; Caillois, 1961). In the case of children's free play, creating designs that represented real world objects was their game of choice. [25]

Game 1 explained through calculation. The calculation that occurs during this play can be understood through the schema $x \rightarrow x + t(x)$. In many ways, this is the full game; you can't help but to do this schema, but restricting it opens the possibilities. Because all of the shape pieces are identical, one can understand this game as the copy and translation of several pieces along the table. Each shape piece is free to rotate 360 degrees, can be reflected by flipping the shape over, and can perform a transformational horizontal and vertical movement anywhere on the table. These represent the "kit of actions" necessary in playing in this open system.

5.4.2 Game Phase 2: Pattern Card Game

For phase 2 of game play, I introduced new game mechanics and components. Players are presented with 60 different pattern cards, having a unique design on each of them. The design on each of these cards is created by using exactly four shape pieces. Once players select one of the pattern cards, they take four of the shape pieces and begin constructing the design.

The pattern cards bring a special dynamic to both play and the emphasis of algorithmic thinking. As artistic elements in themselves, they present some aesthetic value to the players. Children often picked cards from the deck that looked "pretty" or "cool" to them. Beyond the aesthetic value, each pattern card holds a rule-based algorithmic solution to construct it. The cards can be categorized into three classifications based on the number of rules each card uses.

The pattern cards that use one rule to construct it are using the rotational transformation schema $x \rightarrow x + t(x)$. The initial shape piece is duplicated recursively and rotated around a fixed pivot point, resulting in a series of like designs. Although each of these one-rule pattern cards visually look different, it is important to note that they each have a shared schema (Figure 5.23). The transformation "t" uses the rotation transformation carried out recursively. Anyone can trace over the patterns to see that this is correct.

---

[25] The Shape Game seems to echo the "Forms of Life" as identified by Froebel. Froebel's Gift configuration categories included "Forms of Life." The house was one such form of life.

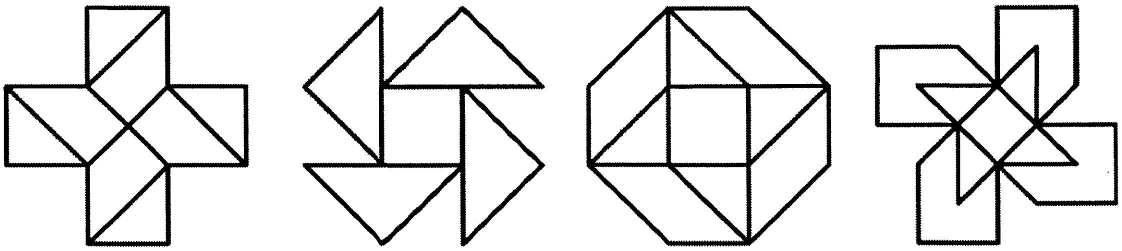

Figure 5.23: One-rule pattern card examples using the schema: x → x + t(x)

Pattern cards that use two rules rely on reflection (Figure 5.24). The two-rule pattern cards are combining rules so that, once the first rule is applied, a second rule is applied to the same base shape. The first rule applied uses the schema x →x + t(x); the solution then is completely forgotten as a second rule is applied on top of the existing composition. The same schema x →x + t(x) is applied to the shape variable building up the complexity of the final composition. The two rules are use the same schema applied differently on each computation pass. Again, these can be traced to test out the calculation.

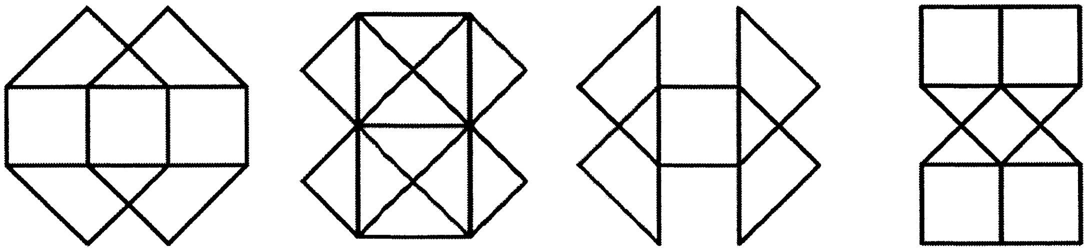

Figure 5.24: Two-rule pattern card examples using the schema: x → x + t(x)

The transformation "t," shown in the previous examples, uses the reflection transformation or rotational transformation at 180 degrees (depending on how you see it). This could be substituted with either a translation or rotational transformation at a different angle to yield alternative compositions.

Pattern cards generated by the usage of three rules may be the most generous of the entire set (Figure 5.25). While the rules of creation may be clear when designs are restricted to one or two rules, the patterns generated by three different rules are the most ambiguous.

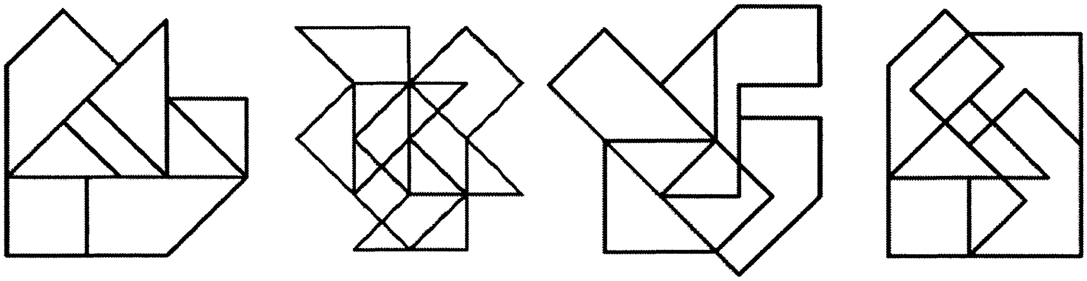

Figure 5.25: Three-rule pattern card examples

The transformation "t" shown in Figure 5.25 may take the form of any of the three isometry transformations. The pattern cards that use three rules to create the composition may use the rules at random, but interestingly enough, they create some of the same emergent shapes seen in the pattern cards that use one and two rules.

Although the previous descriptions of the shape cards show how compositions can be organized by the generating rule, the pattern cards could also be organized by what our eyes see. Classifications of families may be created in these pattern cards through the likeness of emergent shapes. Some compositions produce emergent triangles and squares, while others produce pentagons and rhombuses. Additionally, there is the overall outline of the compositions that produce octagons, crosses, and pinwheels. The artist is free to use whatever the eyes see.

Game Phase 2 explained through calculation. Embedding shapes upon each other is essential to play this game; however, this was not apparent to all players in the study. Some players looked confused and said the task was impossible with just four shape pieces. Children were also seen looking through the pile of game pieces for shapes that matched the discrete geometries seen on the pattern card. *"I need a triangle piece,"* one child proclaimed in frustration as she looked through the pile of identical shape pieces. But she was not misguided; embedding is part of the play!

Similar to embedding, the use of rules for finding solutions to the pattern cards was not intuitive to all players. During free play, players made their own rules to creatively generate compositions; this was sometimes lost when the players began looking at the compositions on the pattern cards. Often, the players went about solving the pattern cards by sequentially laying down each shape piece in search of the embedded shape's location. They were not thinking systematically on strategies to solve the various pattern cards that they were seeing. We will next discuss a third version of play (Phase 3) that was designed to help challenge the players to move towards a more algorithmic approach to solving the pattern cards.

Embedding is a critical concept to grasp in the mastery of visual calculation. These cards allow players to transform the shapes on the cards in ways that would not be possible using a combinatorial system like Lego. Furthermore, due to the "flatness" of the line quality, new shapes can emerge that completely overpower the original base shapes. The original shapes begin to disappear as new shapes emerge. This, of course, does not rule out combinatorial play. Connecting pieces as units is often the first step of discovery for children. They will begin to see new forms appear through playing and manipulating shape cards.

5.4.3 Game Phase 3: Rule Dictation Game

To bring to the forefront the idea of rules and the algorithms that were behind each of the pattern cards, a third mini-game (Phase 3) was developed. We wanted to create a game that made the learning visible to the researchers (or future educators), as well as to the players themselves. To play this version of the game, players need to be paired with a partner. This can be played leisurely or competitively against another team of two.

To begin, Player 1 picks up a pattern card and studies it without revealing it to her partner (Player 2). At the start of the round, Player 1 gives an instruction to her partner on how to construct the composition on the card. Player 1 has to find ways to communicate both the placement of each game piece as well as what she sees on the card. Player 1 is restricted to the use of only words, while Player 2 listens to the instruction and begins constructing the design. When the composition is completed, Player 1 flips the card down on the table to "hopefully" a successful match.

The wonderful thing about this game play is the way in which it forces the players to construct the algorithm as a set of instructions. Likewise, it allows flexibility on what is dictated, by calling out certain emergent shapes as indicators that the composition is progressing in the proper direction. Players all have the same shape cards but may be talking about rectangles, triangles, and squares, none of which are original variables in the set. Through this game play, we can clearly see and hear algorithmic and system thinking.

Game Phase 3 explained through calculations. The previous phases of the game were all built around visual calculation. While the hands are the means to carry out the computations, the eyes are the ones that calculate. With this phase, we introduce both speaking and hearing as key components of calculation. Something like the diagrammatic model of thought created by Kenneth Craik and expanded on by Stiny and Gipps (1978) could help explain the differences in the various phases of game play.[26] In Phases 1 and 2, the model shows that we go through the cycle of seeing, interpreting, and making. This is a fully internalized loop in which interpreting is the same as calculating, and making with the hands is the same as carrying out the computation. Phase 3 of game play breaks the model by substituting the making with speaking. This is, of course, interpreted by another person through his ears (as opposed to his eyes), and finally the computation is carried out by the other person's hands.

---

[26] Stiny and Gips use Kenneth Craik's model of thought (as accepted by psychologist and computer science) to build their own model to explain the structure for a "design algorithm." Stiny, G., & Gips, J. (1978). *Algorithmic aesthetics: Computer models for criticism and design in the arts.* Berkeley, CA: University of California.

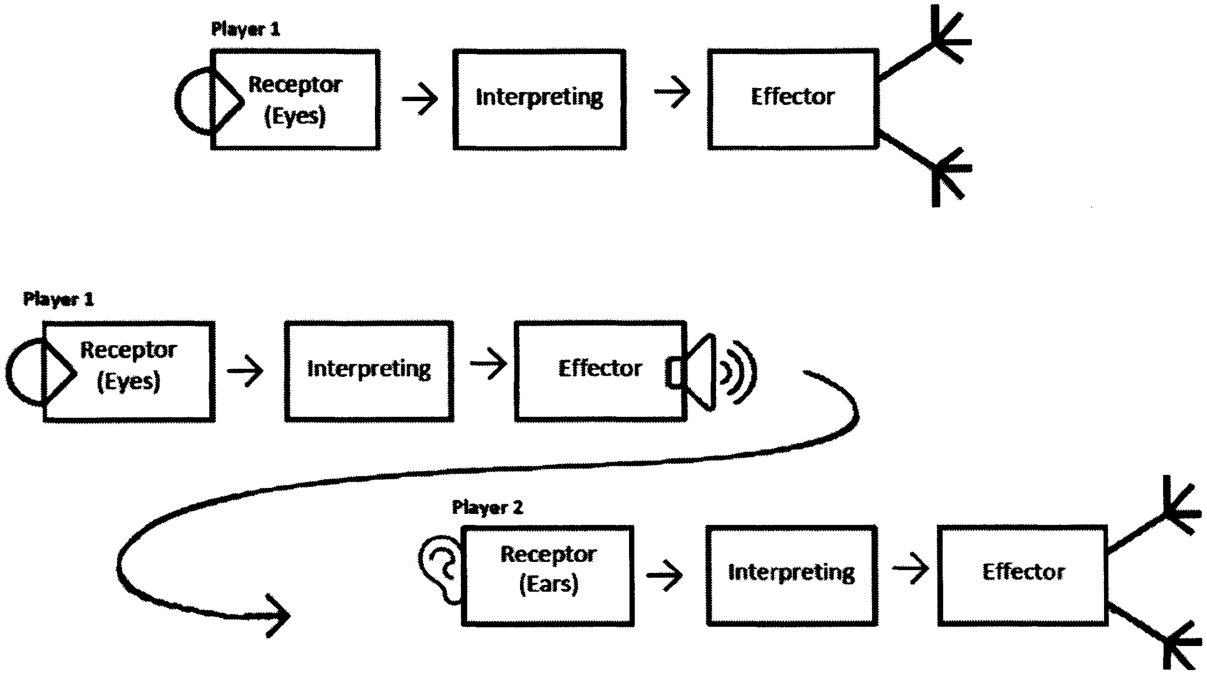

Figure 5.26: The communicative model for Phases 1-3

By changing the task of the first player to speaking rather than creating with her hands, she is still creating. She is creating the set of instructions, the code, the algorithm. The game has changed, but it still is, nonetheless, a creative endeavor driven by calculation.

5.4.4 Game Phase 4: Colors and Solids

A final version of the *Shape Game* is a version of Phase 2 that included a pattern card deck of solid, filled in shapes rather than line compositions. Each of the pattern cards would have a different assigned color, and the task would be the same as the one in Phase 2. Players are presented with 60 of these different colored pattern cards. The design on each of these cards is created using exactly four shape pieces. Once a player selects one of the pattern cards, he takes four transparent shape pieces and begins constructing the design.

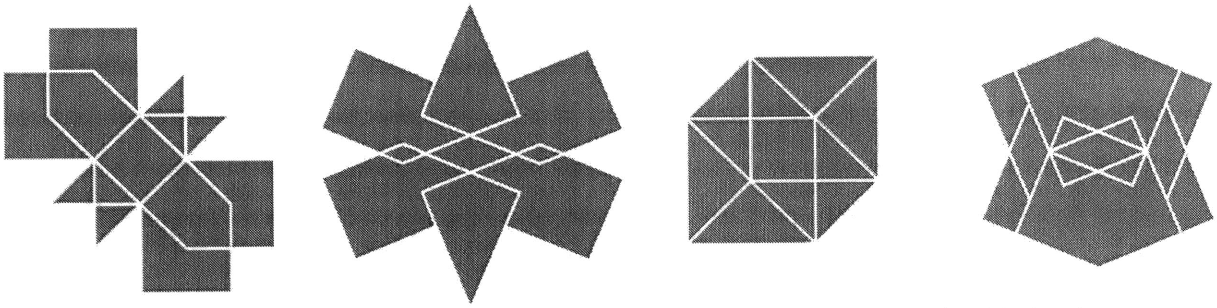

Figure 5.27: Different designs created using colored pattern cards

Under these circumstances, the lines on the pattern card appear to be white and completely disappear into the pattern card's white background on the edges. Another thing the color does is create the illusion of the composition being a solid whole rather than a composite of smaller pieces. Color has a way of stimulating the eyes for children and softening the black and white compositional play in the previous phases.

Game Phase 4 explained through calculation. This phase of game play brings into light the dimensionality of the composition. Previous phases of the game never prompted the player to see this as a game of planes so that he understood the shape had a boundary and an empty plane fill.

The schema x→ x+ b(x) communicates the transformation of a shape when the boundary is articulated around the shape to become a part of the new shape.

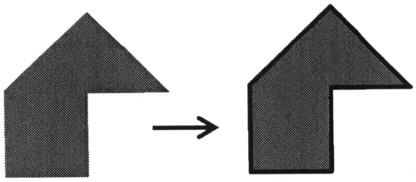

Figure 5.28: The transformation of a shape

Secondly, the boundary color assignment is transforming from white to black. In playing this phase of the game, players are doing both by looking at a color-filled solid shape and replacing it with a shape comprised of the boundary of the shape and the removal of the solid fill. So if we think of the color pattern cards as having white boundary lines and color fills, we can see the above rule in action in Figure 5.29.

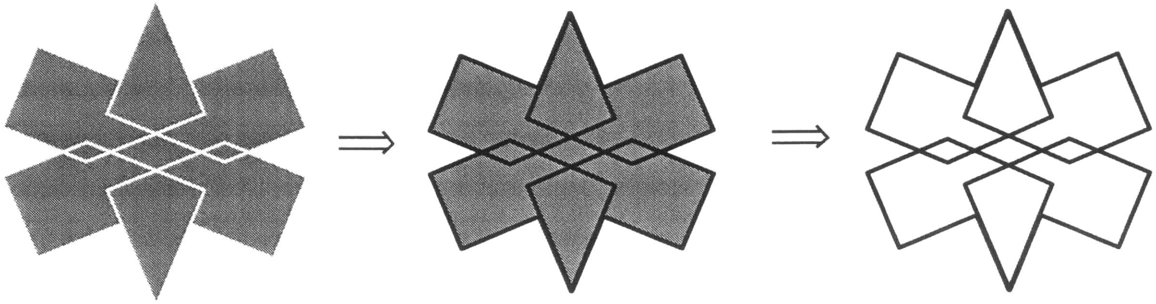

Figure 5.29: The color assignment rule in action

Chapter 6

Children Game Play Analysis

6.1 Data Collection and Analysis

The methods to collect data from these studies followed common practices in ethnographic field studies (Davies, 1998). This qualitative method of research places the researcher inside the experimental experience and tells the story through his own eyes. The role of the game facilitator is included in the study, as we hope it begins to shed some light on the role of the instructor in creating playful learning environments. As an active participant, the researcher tries to give a rich account of the people, places, and practices of the community in study. Ethnography is always an interpretive approach with a focused perspective; it is a sketch not a photograph.

Over a five-month period, observations were conducted accompanied by field notes in the Boston Children's Museum exhibit space. The field notes were later compiled and analyzed to articulate findings collected from the observations. At the same time, some visual records were taken in the form of photographs. The process was challenging, as using such visual recording devices can produce disruptors. Strategic placement of the equipment was required to capture key moments, while at the same time trying to promote the most natural environment for these studies to occur.

This research relies heavily on grounded theory to analyze the collected data. Writing narratives of the accounts we observed were essential to understand the actions and behavior of the observed subjects within the context and placement of the study (Emerson, Fretz, & Shaw, 2011). Through this analysis, we hope to see connections and to answer several questions we have about the relationship play and calculation have on the creation of visual art.

One question that I wanted to answer in this study is, does any learning happen with this form of play. If so, what things are the children learning? Playful calculation is meant to promote algorithmic and system thinking. Embedding is meant to be generous for artists; it is a method of calculation that allows artists to see whatever they want to see (Stiny, 2006). While schemas give suggestions on ways to see a particular composition, they do not lock you into seeing things in any fixed way. This makes calculating a natural form of visual play. Initial studies of the *Shape Game* showed that players identified the emergence of new shapes with every play of hand; their eyes trace, flip, and manipulate shapes on a page unlike the discrete Newtonian way of seeing shapes as "0-dimensional" elements. As we hope to show, the *Shape Game* requires "flexible-vision" to play successfully; the more ways you see, the further you advance in game play.

6.1.1 Field Study Locations

Two pilot studies were conducted to "play test" the *Shape Game*. The purpose of this test was to collect initial data on the playability of the game and refine the actual game mechanics for various field sites. The first play testing took place with 15 students from the Design and Computation research group in MIT's School of Architecture and Planning. On Thursday evenings, this group holds its weekly forums where they come together for lectures and presentations from individuals both in and outside the group. I was given the first of these forum meetings for the fall of 2013 to present the *Shape Game,* and allow the group to playtest it for feedback. The session took a little over one hour in its entirety.

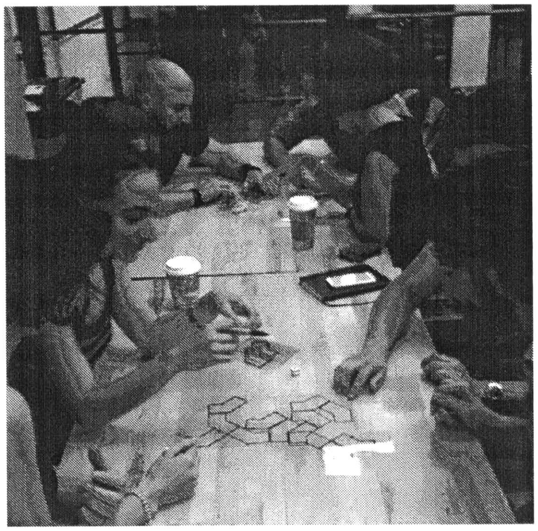

Figure 6.1: MIT School of Architecture, Design Computation weekly forum

Figure 6.2: Hampton University School of Architecture undergraduate design studio

The second play testing took place in a design studio at Hampton University's Department of Architecture in Hampton, VA.[27] As an invited speaker for their fall lecture series, I was also given the opportunity to do hands-on activities with the first-year undergraduate architecture studio. The studio had 34 participants and took a little under two hours to facilitate the full activity.

In both test groups, I opened the session with a game exercise called the "Word Game" to both prompt the participants into a spirit of play and to introduce the concept of co-creation. Students sat in groups at separate tables in a configuration that allowed them to see each others' faces. The introduction activity asked groups to co-construct a sentence by each individual saying only one word. Participants took turns building on the words given by the players preceding them until inevitably a participant placed a period or some punctuation to finalize the round. After playing a few rounds in their groups, we had a short 5- to 10-minute feedback session where we talked about the mechanics of the activity as well as the experience of playing it.

The activity is combinatorial. Individuals simply add words to make a sentence, but it does do a few things well. First, it brings players into the magic circle. In the case of the architecture studio, students were not accustomed to "playing games" as an academic activity. While the design computation students did come with a higher expectation to "play," they were more

---

[27] Hampton University is a private university classified as an HBCU (Historically Black College / University) that maintains a mission of celebrating and preserving African-American heritage. The University's ties to VTRIP (the Virginia Tidewater Regional International Program) provide further skilled assistance by sharing resources among universities of the Virginia Tidewater Consortium to help make International programming possible. Hampton University is very conscious of diversity issues and plays a critical role in racially diversifying the Architecture profession. Hampton University is one of just seven Historically Black Colleges and Universities in the US that fosters black architectural talent by providing accredited architecture degrees. Even today, 45% of all African-Americans studying architecture in North America's 128 accredited schools of architecture choose to enroll in these seven HBCUs. According to the Directory of African American Architects, co-authored by Brad Grant, roughly half of all black licensed architects in the US attended an HBCU. This work is imperative considering the established race and gender inequities in the architecture profession.

inclined to do so as the forum's session had been advertised with the title "Computational Play." With both groups, I found that the introduction activity induced laughter and amusement, two key indicators that people were both playing and having fun.

Secondly, the intro activity is a great prompt to understanding the relationship between rules and creativity. In the case of this sentence-building game, the underlying rules were that each person could only add one word (or punctuation), and secondly they had to follow the conventions and structure of the English grammar. With these both in play, the participants were able to rapidly come up with fun and imaginative sentences. Individuals became a part of the collective whole, while as a group they began to develop meaning with each new added element.

When we transitioned into the *Shape Game,* participants quickly made the connection from words to shapes as they already understood the game mechanics of Phase 1. Instead of offering words, they were prompted to select a shape card and lay it down. Each group was given a unique deck that contained copies of one shape. With very little prompting, they entered back into the "magic circle" and began to play.

My initial concern with using the introductory game before the *Shape Game* was participants would treat the shapes in the same combinatory fashion that they had to place the words. However, the physical properties of the game pieces made embedding a natural game move. Players instantly began to use this technique to pull out patterns and designs of great variety. Similar to the initial game activity, laughter and verbal excitement were indicators that they were once again in a spirit of play.

The core study for this research was ultimately conducted at the Boston Children's Museum in Boston, MA. The Children's Museum is home to one of the most exciting and playful learning environments in the US. Founded in 1913 by the Science and Teacher's Bureau, this center continues to engage children of all ages to come play, explore, and learn. The exhibits in the museum are mostly hands-on and range in subject material from literacy to science and mathematics. Experiential learning is a priority for the Children's Museum, and the curators go to great lengths to ensure that the experience is memorable for every visitor.

Conducting this research at the museum provided many affordances. The museum has a long history in research areas centered on developmental child psychology. As a result, protocols are already set in place to allow researchers to conduct studies in several of the spaces sanctioned by the museum. Often, these studies become resources for other educators and students wishing to advance their areas of knowledge on child education.

Because the museum is open to children of all ages, I was able to observe a wide range of users playing our game. Younger children (between ages 2 and 4) seemed interested in the tactility of the game components. At this developmental stage, the kinesthetic and the tactile are more important than exercises of the visual (Singer & Revenson, 1996). This was also true with children who had certain developmental handicaps. On the other hand, there seemed to be a more mindful approach in the play of older children. Ages of the participants were not documented (to avoid disrupting the natural flow of the museum), but from our observations, children that appeared to be between the ages of 6 and 10 were most enthusiastic in playing with the game pieces.

Parents were another factor that had a great effect on the study. Often, they were seen trying to coax their younger children to play the game and looked toward the observing researcher, saying things like, “Johnny is great at puzzles.” This seemed to be code for, “My child is smart.”

A third location of study was conducted in the context of teacher training seminars.

6.1.2 Observation Methods

Memo writing was the primary way to capture the findings collected from the research. The Boston Children’s Museum carries strict protocols for using visual and/or audio recording to take photographs and/or video of young children. Furthermore, it presents great challenges in the process of using such visual and audio recording devices as they are often disruptive to the research environment. I wanted to capture play in its pure form, and it is often challenging to get children to play when they know they are being watched. Suddenly, they begin to perform.

In lieu of these devices, I relied heavily on the note-taking of both myself and an MIT undergraduate research assistant hired through the MIT Undergraduate Research Opportunity Program (UROP). In taking notes, we wanted to pay attention to several key factors that would then be very helpful as I began to build theories on the observations:

1) What was the gender of the player?

2) How long did the child play? These were generalized as very short (less than a minute), short (1 to 5 minutes), brief (5 to 10) minutes, and long (over 10 minutes). For children playing at a children's museum (with a lot of exhibits to see), anything over 10 minutes is extraordinary. The amount of time, or why the child stayed so long, was not important to me in this research, but was helpful data for me as these long periods of time allowed me to see to what level of thinking the player was able to get.
3) What was the relative age of the player? Once again, we decided not to use formal questioners as to not disrupt the natural playfulness of the study.

The next two components of the notes were the most important part of the data to be collected.

1) What was said? This included the words and facial expressions expressed by the players. I should say here that we were able to take notes at a distance and, in some cases, wrote down the accounts immediately after the observations as opposed to standing, hovering over the child with a clipboard as a doctor would examine a patient.
2) What was done? This included the type of activity the children engaged in with the pieces, the type of composition they created, the categories of hand gestures they used to play with the shapes, and the way they interacted with other players.

All of these sections (particularly the last two) were very essential in establishing what happened in the study to draft narratives that I will use to communicate the playful calculation of these children playing the *Shape Game*.

6.1.3 Documentation and the Use of Narrative

> *Narratives are produced and performed in accordance with socially shared conventions; they are embedded in social encounters; they are part and parcel of everyday work; they are amongst the ways in which social organizations and institutions are constituted; they are productive of individual and collective identities; they are constituent features of rituals and ceremonies; they express authority and expertise; they display rhetorical and other aesthetic skills.* (Atkinson & Delmont, 2006, p. xxi)

Using narratives to convey the complex environments and activities of a culture has proven to be a successful research method. Donald Schön did this in his own writing, illuminating the culture and practices within design education. Narratives help capture a series of events far more effectively than lists charts and graphs. It's why I have chosen this method to convey my observations of the *Shape Game*. While these selected narratives do not represent the entirety of all that was observed, they do represent different categories of similar stories. These are micro events that can be scaled up for a larger macro understanding of play and calculation.

6.2 Game Play 1 (Ethnographic Narrative)

One of the first players of the *Shape Game* was three-year-old Taylor. One afternoon, she was playing with a prototype version of the game on a small table. As she began moving the shapes around, she proclaimed, *"Look a diamond!"* By this age, Taylor was very much into shapes. She knew her basics: the square, circle, triangle, rectangle, and diamond. Looking down at her configuration, she began to slowly pull the shapes back and forth, all while making the emergent diamond grow and shrink. Effortlessly, she moved the overlapping pieces closer and further from each other.

For Taylor this moment was visually magical, but at the same time, little to her knowledge, she was constructing her own rule. As she performed the translation of the two shape game pieces, she was controlling the scale of the emerged "diamond" shape. Through her play, Taylor discovered her own parametric rule based on the schema $x \rightarrow x'$. The notation x' refers to parametric applications of rules that fall into a range of similar transformations. In Taylor's case, the horizontal translation of the shape provided the range of actions needed to make her diamond "grow."

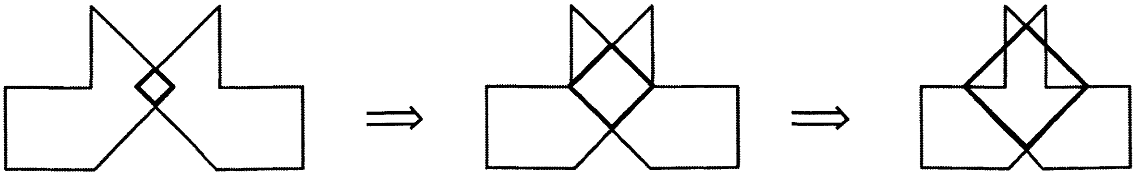

Figure 6.3: How to find a "diamond"

The amazing thing about this instance of play was her discovery of a rule that involved a scaling transformation. This could only be articulated if she placed visual emphasis on the emergent shape. If players only focused on the original variables, they would only see the translation rule at play. Secondly, she was very aware of the relationship between the design action and design composition. When Taylor wanted to find a diamond, she knew what she needed to do to create it. She knew the rule, and the rule did not include composing discrete lines that made up the edges of the desired shape. Taylor had discovered that shapes could be made using other shapes through embedding. Playful calculation is full of these visual moments that allow us to artistically see whatever we want to but can still be formally explained through a set of rules.

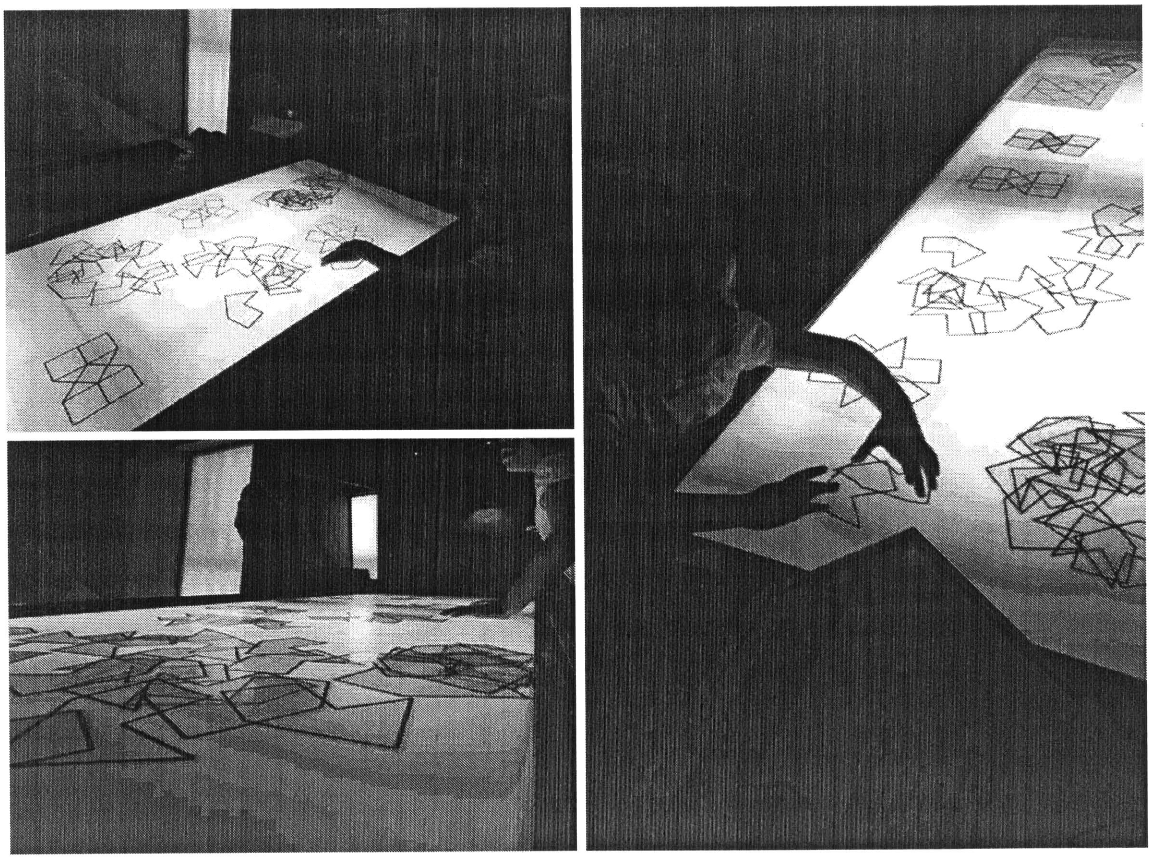

Figure 6.4: Boston Children's Museum

6.3 Game Play 2 (Ethnographic Narrative)

A family of six came to the light table (father, mother, daughter, two sons, and grandmother). The father immediately perceived the strategy of embedding. His first gesture was to pull the shapes and place them in ways to create the patterns on the cards. The mother was completely opposite in that her first action was the typical combinatorial play mode. She even admitted that she "doesn't see the same way [her] husband does." The daughter took to putting pieces on top of the pattern cards to see how they embedded into the compositions. The son's first play was to create symbolic forms. "I made a ninja star," he proclaimed after finishing one composition.

The most remarkable experience happened after observing the father and grandmother compete in solving the pattern cards. During their play, they seemed to move to some competitive *agôn,* which was observable through their playful banter. "You got it from me," jokingly proclaimed the grandmother. As they were playing, there was one pattern card in which the father completed but the grandmother was stuck on. Eventually, one of the sons decided to jump in and attempted this pattern card as well.

After solving it, he proclaimed with joy and began to communicate his process of solving it to his grandmother, "You do it like this." With that, he began to manipulate the shape pieces. "You make two crowns." He demonstrated how to make a shape of two cards with the cards on the table after which he labeled the composition of two cards "a crown" and then duplicated it. "Then you slide them together like this."

He took one of the crowns and reflected it from the other and proceeded to slide them together. Looking up, he smiled as he had now not only solved the pattern card but came up with a clever way to explain the procedure. This clearly demonstrates the player's ability to see the embedded shapes within the composition as well as the player's discovery of the rules used to generate the composition (Figure 6.5).

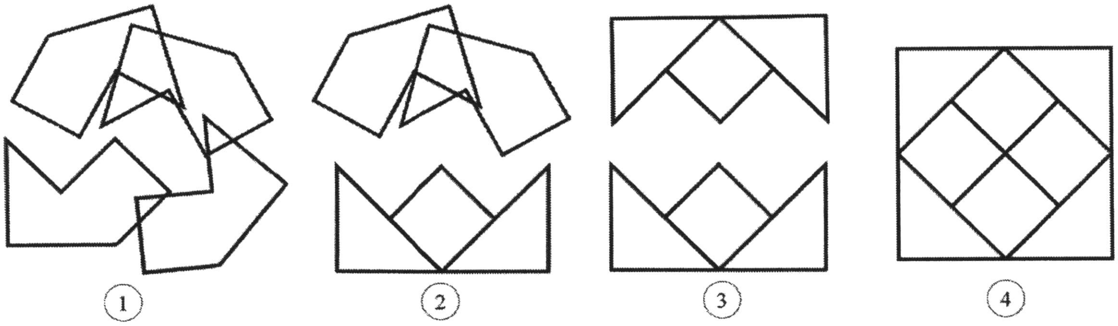

Figure 6.5: The stages of composition, using "crowns"

6.4 Game Play 3 (Ethnographic Narrative)

During one of the sessions, we decided to change the venue from the large light table to a series of smaller tables, each with a 4' x 4' surface and standing at a standard height. The tables were each colored differently in bright pastel colors (magenta, blue, green, and yellow). The decision to move to these tables was first out of necessity; often times, when the museum was crowded, it was hard to shut down the light table to set up the *Shape Game.* However, once we began to use the small colored tables, we found them to be just as effective. Additionally, they offered a more inviting atmosphere for children and parents to sit down and play. On average, parents and children sat twice as long on this set up than they did with the light table.

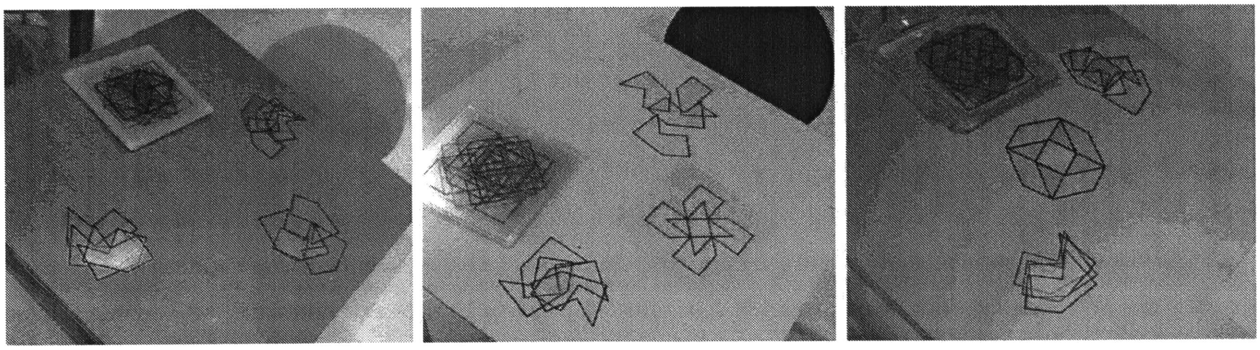

Figure 6.6: Playing on colored tabletops

Jessica (around age six) came to this new set up and immediately began playing with the shape pieces. Her mother sat down beside her and began working with the shape pieces herself. On the table sat the large pattern cards as well. The pattern cards used at the museum were much different than ones we had previously fabricated, because they were also printed on the transparency film. "What's this?" the little girl asked holding up the pattern card. As researchers we tried not to interfere with the subjects, but periodically we took on the duties typical to the other museum staff. We briefly explained that this was a game in which children could either make up their own compositions or they could take four pieces and try to solve one of the pattern cards.

As Jessica continued playing, she began to master all of the geometric transformations. She would slide pieces along the table in translation, utilize her fingers to spin a card in rotation, and even flipped cards back and forth exploring the reflection rule. She seemed very amused, making houses, stars, and various other compositions—even naming them out loud to her mother. Finally, she transitioned back to the pattern cards. For this little girl, she was not interested in solving the pattern cards but more into manipulating the cards as they were one of the shape pieces themselves. Suddenly, she began taking the transparent pattern cards and began making elaborate designs by performing the same actions on the cards as she had done with the smaller pieces.

"I don't think that's how you play with these," her mother said. I smiled and assured her that her daughter could play with them in any way her imagination would take her. After a bit of fun working with the pattern cards, Jessica did succumb back to her mother's wishes and began to work on solving some of the designs. I could tell that for her this was a bit more limiting than her previous activities; nonetheless, she was being diligent in performing the task.

Just as she was about to finish one of the pattern cards, Jessica began to drift into a new play discovery. She had lifted the card off the table and realized the card's line had produced a shadow on the table. The shadow lines were almost as dark as the pattern card lines laid on the table, but the further she lifted the card up the larger the shape grew. Jessica had discovered how to scale the shapes! Previously, scaling had not been thought of as I believed the physical properties of the game only enabled for the isometry transformations of the pieces. If we had not changed the set up for these smaller tables that happened to sit under the bright light canisters casting these shadows, the scaling feature would never have been discovered.

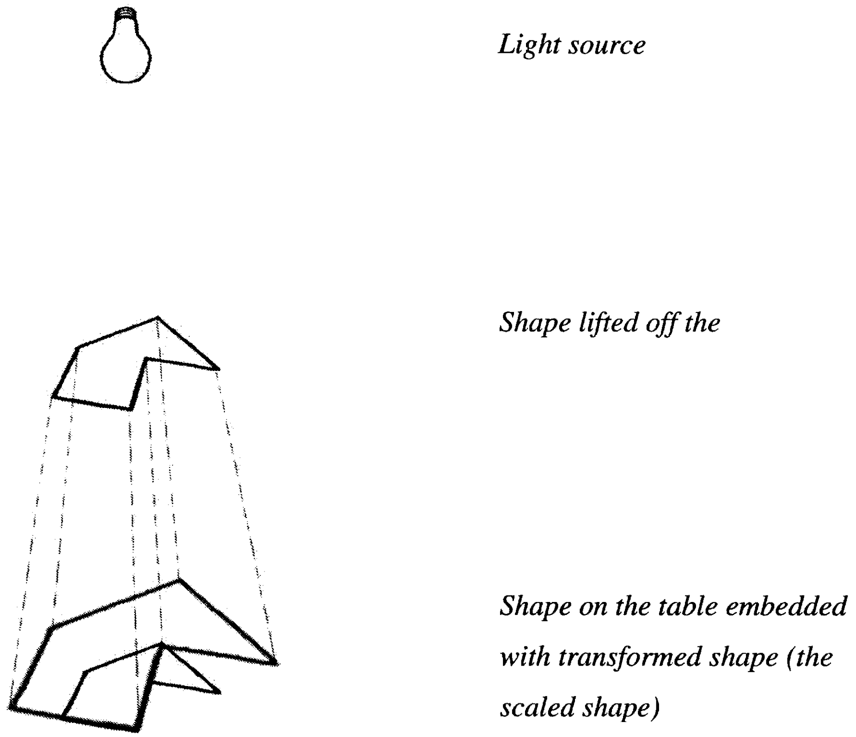

Figure 6.7: Discovering the scaled shape

6.5 Game Play 4 (Ethnographic Narrative)

I took the *Shape Game* to the STEM to STEAM training seminar I conducted for the instructors that would be teaching in the 2014 MIT STEM Summer program for middle school students. I was tasked with giving a presentation on how the instructors could make their curricula more "artful" for the students this year. Every summer MIT hosts this program for children between grades five and eight, allowing them to take classes in subjects that range from algebra to statistics. The majority of the instructors are undergraduate MIT students who had never taught before, and their first inclination was to present the children with age appropriate problem sets. Part of my objective was to get them to consider a design-based curriculum that integrated the subject matter through hands-on projects. Secondly, I wanted to let them know that they could explore all aspects of design (even aesthetics) through rules and calculation. I could think of no better way to acclimate them to the idea of playful calculation than by letting them play the *Shape Game.*

To begin, I asked the teachers to separate into teams of two. The arrangement of the classroom allowed for each team to sit so that the players were facing each other with a narrow table between them. I then asked them to decide who would be the “rule dictator” and who would be the “shape constructor.” Once they decided on their player roles, I began to hand out their play materials. To the constructors, I gave each a closed envelope with the game pieces; for the rule dictators, I gave a shape card faced down so that they could not see the composition. Some of the members released nervous laughter as the tension of “not knowing” built with their anticipation to begin playing.

The first instruction was for the players holding the faced down shape card to inspect it quietly without communicating to their partners or showing them the composition. I then told them that their partners had the pieces necessary to make that composition they were looking at and that they would verbally give them the instructions to make the composition. There were several engineer majors in the room who snickered with confidence. Although there was no prompting that this would be a competition, it was striking to see that they instantly began boasting of who would finish first. It seems *agôn forms of play* have a way of developing entirely on their own.

When I gave the signal, the shape constructors opened their envelopes to find their pieces. “Are you serious!” one of the rule dictators said as she saw the pieces. “This can’t be right!” another teacher proclaimed. The shape constructors were quite confused at this outburst because they had no clue what the design on the card was. I saw a few of the participants rechecking the envelope as if there were missing pieces left inside it. While I gave them no instructions on how to begin the process of dictation and construction, I did reassure them that they had the necessary components to complete the task.

This seems like somewhat of a cruel task and rightfully so. It is almost a game of misdirection and deception. When the teachers were given the time to inspect the cards without seeing the corresponding pieces, they were drawn to the discrete shapes in the composition. Because they were expecting to give instructions on how to construct, they were naturally trying to tally all the pieces. Once they were presented with pieces that they did not expect, they had to rethink the entire task.

It was interesting to hear the types of commands the rule dictators were developing as they played this game. The obvious commands like, "slide that piece there," "flip it over," and "rotate that one" were as expected in communicating the actions needed to perform geometric transformations of the pieces. But in order to communicate the proper formation of the composition, dictators were relying on what their eyes saw. I took note of the players given instruction on what to do with triangles, rectangles, and "houses," none of which were initial pieces handed out. As the players began to see the emergent shapes, these became the basis for communication.

All of the teams did not succeed in the task; others finished and were able to work on a second design. After 30 minutes, I instructed the unfinished teams to reveal their pattern card and work together. The activity ended with a discussion concerning the nature of the use of rules in design. Many of the participants had not yet realized that they were each working on different designs using the same shape components following different rules. Other groups compared their designs and realized that their instructions were very similar although their designs did not look the same.

"It's hard to believe that this simple shape can make all these different designs." One teacher said. "I wish they had taught me this in school," said another. After doing this exercise in a variety of contexts, I have come to realize that engineers are often very excited to learn they can explore aesthetics through the use of rules and schemas.

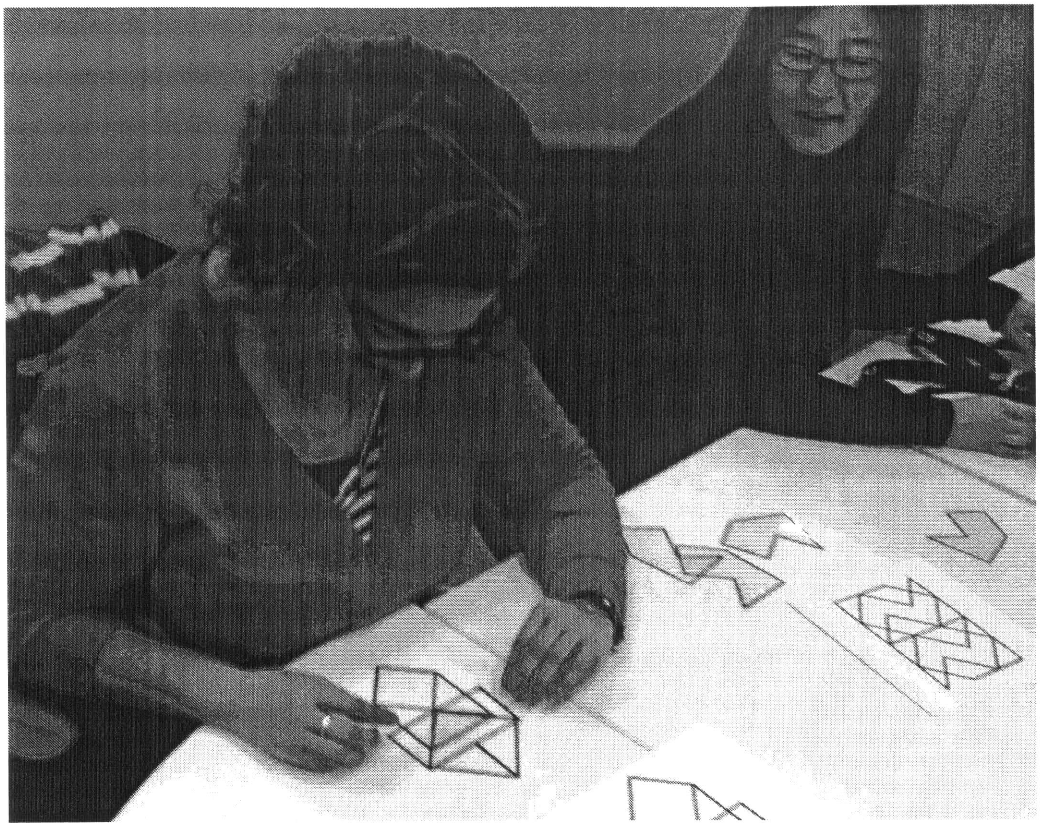

Figure 6.8: Play session at the MIT Media Lab

Chapter 7

New Theories on Visual Calculation

Although shape grammars remain a "specialty" in the art and design world, the principle functions of the enterprise can be seen in the play of children. While children playing the *Shape Game* did not recount the various geometric transformations they were performing, the rules were still present in their play. The *Shape Game* requires the player to perform several shape rules to solve each of the pattern cards. Each card has a unique set of rules that makes up the algorithm of its composition. Through game play children are actually reverse-engineering the designs by manually carrying out the rules with their hands.

With the exception of "scaling," each of the geometric transformations was applied to the initial shape card to yield the final composition to the player. Children came up with several strategies to carry out these transformations. In many ways, the playful calculation became part kinesthetic as the players used the positioning of their fingers to slide, rotate, and reflect the game pieces around the table (Stiny, 1980). A common example of this was seen when children would often stack several game pieces together and fan them out. This would either be done by sliding them recursively all together or using their finger as a pivot point where they rotated the various copies.

One prevalent question that surfaced during the research was, were the players actually approaching the problem solving algorithmically? Did the players begin to make their own rules to understand the solution to solving puzzles? Or, were they simply exploring by the random placement of game pieces? To understand this further, we observed children playing with the game both without any explanation of *shape rules* and with the brief explanation of *shape rules.*

7.1 Playful Calculation with the Body: Hand Gestures

Tangible learning through manipulatives has a great lasting impact on the learner. The *Shape Game* provided several opportunities for me to see the relationship between learning with the hand and seeing with the eye. The hand play can be understood as the "kit-of-actions" the players use to perform the game. These actions can be further characterized by the unique hand positions players took in game play.

Establishing translation with their hands was the first action done. Translation was performed by sliding the game pieces along the table. Although it would make perfect sense to pick the card up and move it to a new location, most children took to sliding them along the surface of the table. These actions of sliding were done with their fingers: single, double, triple, and open palm (Figure 7.1).

Establishing a rotational point with fingers was the second noticeable action taken in play. This action was done in one of two ways. In the first method of rotation, players used one finger to establish the point of rotation on the shape sitting on the table surface. With their second hand, they would spin the piece to the desired state, performing the rotational transformation. The second method of carrying out rotational transformations is what I have labeled the finger pinch. This is done by holding the shape pieces up off the surface, all while pinching them on a pivot point with the pointer finger and thumb. Once this is done, the player can then spin them around to operate the rotational gesture (Figure 7.2).

Finally, we can look at the various ways the children performed reflection (Figure 7.3). This action was performed just as frequently as the previous two. The player lifts up the shape piece and flips it while paying attention to the shapes left on the table. In many cases, the free hand is holding down the shape that is fixed $x \rightarrow x$ while the second hand is doing the transformation $x \rightarrow t(x)$. Both hands together would allow for the schema $x \rightarrow x + t(x)$, where t contains a reflection.

For example, there are lots of ways we can teach geometric transformations, shape grammars, and schemas. The traditional way to teach mathematics in a K-12 curriculum involves blackboards, chalk, and a lot of graph paper. As the teacher draws on the board, the students mimic on their drafting paper the different isometry transformations. This method of instruction requires a higher level of thinking for most. Instead, we position this instruction much later in K-12 curricula. The building blocks to understand these concepts, however, can be found in the playful inquiry described in the *Shape Game*. During this play, children are discovering the basic transformations on their own and with their own definitions. Translation is informally called sliding.

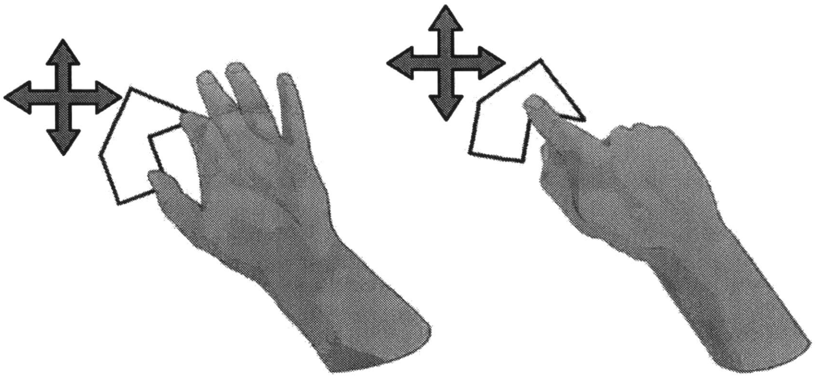

Figure 7.1: Translation performed by sliding with the fingers

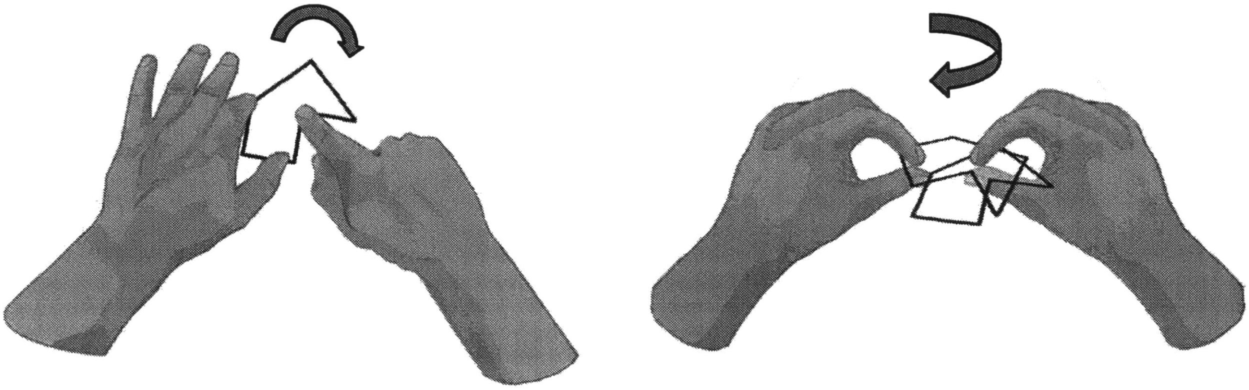

Figure 7.2: Establishing a rotational point with the fingers to complete the rotation

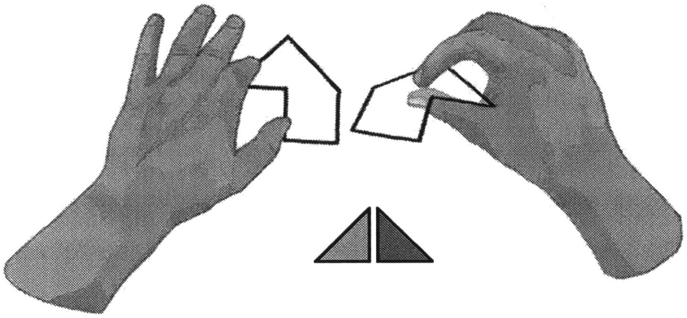

Figure 7.3: Performing reflection using the fingers

Rotational transformations may be spinning, and the reflection transformation is playfully "flipped like a pancake." The usage of the hands to discover the possibilities of the game, coupled with the children's freedom to express these gestures with names of their own, is a model for constructivist learning in K-12 mathematics.

Piaget notes that as the child develops, learning with the hands was essential. The connection a child's hands have with any toy is a beautiful dance of control and imagination. For children playing with the *Shape Game*, the hands are intuitive tools to carry out calculation. This is at the core of what Terry Knight calls *"slow computing"* (Knight, 2012). In this teaching approach, shape grammars are not taught through formal lectures but rather done through doing, making, and play. Hands and eyes become the instruments necessary to carry out computations. Playful calculation extends beyond the visual to the tactile.

We all know that hands-on inquiry can lead to experiential understanding of material and shape qualities of a subject matter. But what can the hands tell us about the geometric transformations of shapes? The strength of hands-on inquiry in understanding shape rules is the ability the user has to discover all of the in-between stages of a transformation. If we apply, for instance, a 90-degree rotation to a shape via a computer-based system, the shape would just snap into its new orientation. What we miss, then, is the opportunity to see the degrees of rotation between 0 and 90 degrees. When this type of transformation is applied in the schema $x \rightarrow x + t(x)$, this can lose sight of all of the transformed embedded shapes that evolve during the course of the transformation from 0 to 90 degrees. From hands-on actions and slow computing, we can find so much more.

7.2 Informal vs. Formal Visual Calculation

Play always takes place informally unless it becomes overtly rationalized, in which case it becomes something other than play. Intuitive learning is similar in that it occurs outside of formal learning environments, allowing students to acquire. The proper task of the instructor is to situate the learning environment to allow for this to occur. Of course, this does not rule out scaffolding as a strategy to guide learners to new dimensions of intuitive play. By not doing so, the student may be stuck in the gap created between the place of intuitive learning and formal learning environments.

> *Students who have perfectly adequate intuitive understanding often exhibit great difficulty in mastering the lessons of school. It is these students who exhibit "learning problems" or "learning disorders," and it is their difficulties that have fueled many of the indictments of our educational system. Yet even those who prove successful in school typically fail to appreciate the gaps between their intuitive understanding and*

> *those that are embodied in the notations and concepts of schools.* (Gardner, 1991, p. 10)

If only the students used rules and grammars, perhaps these gaps would cease to exist. Playing with rules gives structure to informal learning, and when used intuitively, it allows for creativity and flexibility.

Recent teaching approaches in K-12 language arts have tried to bridge the gap of natural learning and formal instruction. "*Inventive spelling*" is a new approach that has found its way into elementary schools with some criticism.[28] Through this form of instruction, children are given the task to create short stories without paying any special attention to the "proper spelling" of the words being used. Instead, children are prompted to use any words they choose, all while spelling them in the way they hear the words in their heads. The belief is that the unconventional spelling of words falls under the constructivist framework of learning and promotes creativity and expression in writing over the mechanics of writing.

The intuitive way in which we understand geometry also falls under some type of natural learning. According to Piaget, the child's ability to understand geometry is somewhat akin to the things we find in language acquisition (Piaget, 1960). Before formal instruction, children have intuitive concepts of geometry. None of the tasks created by Piaget to study children involved the concepts of embedding, but the task involving the conservation and measurement of length definitely touches on some parts of visual calculation (Piaget, 1960).

Gardner (1991) further supports the understanding that children intuitively know how to carry out geometric transformations on objects in space.

---

[28] Spelling, in the US, is traditionally taught through rote memorization. Students are presented with a series of words that the curriculum deems "appropriate" for their age group. Students then go about learning the meaning and the proper spelling of the words through a series of drills and rote task. Alternatively, the inventive spelling model places emphasis on the word usage and encourages students to phonetically spell out the words as they hear them. Bear, D. R. (2008). *Words their way: Word study for phonics, vocabulary, and spelling instruction.* Upper Saddle River, NJ: Pearson Prentice Hall.

> *The notion that the world consists of objects that have boundaries, move in certain ways, and have predictable effects upon objects with which they impact—are present at birth or shortly thereafter and do not undergo a lengthy developmental process.* (Gardner, 1991, p. 29)

More recent studies have suggested that children possess nonverbal ways to calculate mathematically years before they are taught formal numeric systems. Apparently, this skill is gained during the child's daily experiences and may be based on a more sophisticated "informal calculation" system than we realize (Butterworth, 2005). Piaget also experimented with the notion of an informal calculation system in the minds of children before formal instruction. Through the observations of tasks that included the conservation of weight, volume, and length, he discovered that these concepts are developed over time (Piaget, 1960).

What all of the previous examples have in common is the exemplification of informal learning as the primary method for children to learn very complex things. Language, geometry, and mathematics all have an intuitive face to them in which children find ways to learn. Visual calculation might also lie within the domains of formal and informal usage. Children perform visual calculation well before they are taught formal ways to algorithmically express their ideas. As shown in the *Shape Game*, children inherently possess the ability to perform geometric transformations, embed shapes, and identify emergent geometries well before formal instruction.

The *Shape Game* was not presented to children as a "task" in the same clinical sense as conducted by Piaget, but it does reveal in several ways the child's ability to discover concepts such as symmetry, recursion, and of course the pleasure of embedding shapes. Embedding is as natural for children as any other natural language, and is mastered informally during moments of play, if they are presented with materials that lend themselves to embedding. For language, this may relate to the mixture and play of the sounds of words rather than playing with the discrete letters or words themselves. Children often create riddles and songs all based on embedding strategies from the sounds they hear in the words.

> *In addition, there's the independent Cartesian hypothesis that rules are innate. Evidently, language and embedding are equally automatic . . . . If our knack for*

> *language tells us about ourselves, then surely our knack for embedding does, too.* (Stiny, 2006, p. 52)

The *Shape Game* was similarly successful in allowing children to play with this game due to the material components that allow for embedding.

Based upon my observations of the *Shape Game*, I might argue that the natural language of 2D and 3D geometry is inclusive of embedding. Froebel was definitely trying to play off of this in his gifts. Although his materials of use did not allow for full emergence, in a combinatorial way the geometries he used often created larger versions of the same kind. Eight cubes made a large cube in gift 5 and gift 7, allowing for the discovery of triangles that created squares. Observing the children at the museum allowed me to see the furtherance of this same type of play. If given the opportunity, children will naturally allow objects to intersect, overlap, and disappear. Children are also experts in pulling forms from other forms or, in some cases, seeing forms from nothing at all. Adults seemed to be the ones most hesitant to this type of play which leads me to think that moves of geometric embedding may be a part of the natural abilities we unlearn.

7.3 Combinatorial Play and Combinatorial Thinking

When Froebel was developing his learning manipulatives, he was primarily interested in how children understood the relationships between shapes and how they associated them with the natural world. Children could place triangles together to make squares. Squares could be arranged to make crosses and so on. The manipulative materials allowed for several compositions to be created, which he categorized forms of life, forms of knowledge, and forms of beauty (Froebel & Hailmann, 1887; Smith & Wiggin, 1895). With each, the composition process was something we label "combinatorial play."

Combinatorial play is a type of play that treats each variable as a 0-dimensional unit. Zero dimensional units are the foundation of all form. In geometry, these are points. They begin the hierarchy of all forms; again there are 0-dimensional points, 1-dimensional lines, etc. One-dimensional lines help create 2D shapes, and 2D shapes can be extruded or combined to create 3D objects. Within each evolution, the variables transition from 0-dimensionality into 3-dimensions. In shape grammars, the individual has the flexibility to move between dimensions. This is done through embedding and rules that articulate the emergent shape.

Combinatorial play ignores much what the eyes see and keeps each individual shape as a fixed 0-dimensional variable.

In a combinatorial system, full blended embedding does not occur, and emergence is limited. The emergent forms that come from combinatorial systems are comprised from only the boundaries of the entire set of components. The result of this type of play results in compositions that are just the sum of their parts (Stiny, 2006). However, when one plays with embedding, the limitations of emergent forms are immediately reduced. By allowing shapes to embed within each other, we find compositions that are greater than the sum of their parts.

The difference between combinatorial play and play that uses embedding with shape emergence can be easily seen when comparing the *Shape Game* with more traditional Froebel tiles. We were able to observe children playing with a similar version of the Froebel gift 7 during our time at the museum. The typical configuration for the light table used in the museum contained an arrangement of colored, transparent tiles of different shapes (also referred to as *Tangrams*). Along with them, there were four transparent pattern boards with black and white lines forming a suggested composition by dissecting a large square into several different small regions. Some children began mixing materials by trying to place the colored tiles on top of the pattern cards from the *Shape Game*. In mixing the two play sets, some individuals took the colored tiles and tried to apply them on the pattern card compositions. They were looking for other pieces to fit the new shapes seen by overlapping and embedding lines. In failing to do this task, one parent communicated to her child, "Sorry, honey, they must not have all the pieces here."

With the *Shape Game,* all the pieces are present. The game is attempting to extend the creative play beyond combinatorial matching and illustrate that by embedding and overlapping you can discover infinitely more geometries. From the perspective of visual calculation and shape grammars, more shapes were visible than the discrete geometries formed by black lines. However, for children, play was reduced to placing the color tiles exactly where they fit on the board. It became a simple combinatorial puzzle. A triangle had to match a triangle, a square a square. In several instances, parents served as the onlookers to tell the child, "No, that's wrong," as if there were a single configuration, a single solution, a single way to calculate, and a single way to see and play. Combinatorial play is not a lower level of play; it's just a game with less maneuvers. It's limiting.

When it was time to remove the *Tangrams* for the *Shape Game*, the period of transitioning one set of materials for the other was sometimes confusing for the onlookers. One parent was very irritated and said that, by removing the color components from the light table, we were removing the "fun" components of the entire system. We never actually removed anything from children while they played, yet it was hard not to feel like the villain for altering their play world – at least to some of their parents.

In seeing the *Shape Game* for the first time, several parents said to their kids, "Do you want to come play with *Tangrams*?" or "Look, honey, *Tangrams*." There could be several reasons for this. First, the light table in the museum is traditionally set up for *Tangram* tile play. Frequent visitors of the museum may be accustomed to that setup. Secondly, the *Shape Game* does involve geometric shape play. So the confusion is understood. However, this preconceived understanding of the game sometimes influenced what parent and child thought they could or should do with the game pieces.

In most children's toys today, combinatorial play is dominant. There are very few learning manipulatives that allow for visual intersection and ambiguity. The mediums that continue to do this the best are those that enable traditional drawing activities. Paint, pencils, crayons, and watercolor all allow for the individual to create in ways that move beyond combinatorial maneuvers. Coloring books reduce this by suggesting a combinatorial perspective on image creation. First, the image has been neatly dissected into discrete shapes for the child. Secondly, most children are told from an early age to, "Color within the lines." Many artists are interested in seeing what happens when you color outside the lines and in-between, and what you see when there are no lines at all.

It was amazing to hear the expressions of individuals of all ages when we demonstrated how the game's shapes could overlap with others to create new geometries. It was as if a magic trick had been performed! This, sparked new interest with players, as they now began to see the affordances of embedding and shape emergence.

7.4 Adults vs. Children's Playful Calculation

The majority of adults who came by to play seemed preconditioned to think of the shapes in a combinatorial manner. This seemed odd as the pieces on the table were always scattered so that lines overlapped and fused with each other. Yet on countless occasions the first gesture an adult player made was to "detangle" the shape pieces so that there was no overlap or embedding. When they began to construct compositions, they then resorted to arranging pieces on the light table in ways that each piece never intersected another. It was like their brain was telling them that these pieces could not or should not intersect. Children, however, approached the game without these restrictions.

What makes adults see and think more combinatorial than children? I don't want to get too far into the domain of habits of mind, but this question of "why" adults are more combinatorial is important when we think about education and learning environments, as adults ultimately play the role of teachers and play facilitators. A few theories have crossed my mind concerning the adult mind and combinatorial thinking.

The first cause may be the result of rules carried over from past experiences in life. Over time, individuals create mental repertoires that they call on when faced with new challenges. These repertories are essential for our ability to join together separate domains of thought in order to perform new tasks (Gardner, 1991). Unfortunately, they can also be the source of resistance to new ways of thinking if the mental repertoires are not used in flexible ways (Perkins, 1986). In the case of the *Shape Game,* many adults were playing a game they had never played, using a mental repertoire based on a combinatorial play mechanic. This resulted in the underutilized play maneuvers and shape designs lacking the richness of embedding and new emergent geometries.

The second theory for combinatorial thinking in play is the mind's desire to grasp visual coherency. In truth, it is easier to understand things as discrete units instead of seeing things as embedded shapes that appear and disappear. Take a simple line bounded by two points in which we can firmly say that there are an infinite number of lines embedded on that simple line. There are also an infinite number of points on the line. Jumping dimensions is not for the faint of heart, and it is easy to get lost once you start doing it. When we begin playing the *Shape Game* and begin to see the wild and irregular shapes that begin to emerge once the shapes overlap and the edges embed into each other, it's no wonder some feel safer by not allowing this to happen. Then again, what's the fun in that? It is lacking a lot of the *alea* and *ilinx,* qualities that make up any great game.

Finally, I question the presence of combinatorial thinking as a result of diminished abstraction or playful thought. This is what happens when clouds in the sky become just clouds in the sky and you can no longer see them with the imagination of a child. When children see clouds, they perform the mental transformation of meaning. The cloud can become a turtle or a dragon, depending on where their eyes and minds make them. This cannot occur, of course, if children are seeing the clouds only from combinatorial perspective. The shapes (and meanings) have to emerge and disappear as you see, to truly play this game.

7.5 Algorithmic Thinking in the Arts

When some artists think of algorithms and procedural methods related to visual art, they often think of the negative effects of "paint by numbers." Painting by numbers is an explicit set of instructions that tell the artist exactly what color to fill in the lines. Although this is a form of algorithmic art production, the system is very rigid and is far from the flexible system of calculating expressed in shape grammars. The painting by number technique only has one rule, and this rule does not involve seeing new embedded shapes. Unfortunately, many approach learning new technologies with the same rigidity. Rule sets should never be closed, and especially for artists they should allow users to hack and extend their play beyond the initial offerings.

A great case study on the noticeable difference of learning infused by playful calculation can be seen in what's being done at NuVu Studio in Cambridge, Massachusetts. NuVu is a progressive alternative education environment that offers advanced courses to high school students. Each course lasts two weeks and ranges in subjects from computer games to robotics, graphic design, and fashion (to name a few). Students enroll in these classes throughout the year. Consistently, this learning center is inspiring minds and challenging our notions of school and learning. For the summer of 2014, the theme was "Fantasy," and I taught as an instructor for the video game studio. Along with my fellow game instructors (a veteran video game sound designer and a recent MIT graduate), we led students along the process of developing their own prototype video game.

In total, there were five projects developed by teams that ranged from groups of two to three students. The students had no previous background knowledge in game design, and only a handful had ever touched 3D modeling software. To scaffold the learning experience, we decided to present them with a video game "kit of parts" that held the components you would find in any 3D or 2D "platformer" game. Students then used this as their launching point to analyze and understand computer code, grasp the hierarchical logic of game assets, and finally deconstruct the kit into unique projects of their own. Through this kit of parts, they were able to understand rules and develop a schema for the relationship between the game objects.

Looking back at the studio, I can see several experiences that stand alone as learning principles for any K-12 learning environment. Video games naturally invite the spirit of play into the learning experience. As mentioned earlier, play essential to learning; it is essential to any creative endeavor; and it opens the learner to flexible thinking (Eisner, 2002; Langer, 1997). Secondly, this studio is built on the pedagogy of "learning by doing" (Dewey, 1938; Hetland et al., 2007). We did not hand out textbooks or give formal lessons on C++ or Java Script (the main computer language used to code games), rather we allowed students to learn the fundamentals of these languages through hands-on manipulation, trial and error, and online resources. They learned quickly how to use online communities to find answers to questions, while embracing "debugging" and code errors as part of the creative design process (Roblyer & Doering, 2000).

Video game design is a great example of play and algorithmic thinking in the arts. The creation of video games requires analytical/algorithmic thinking, math, and technology know-how. On the other hand, the decisions the students made on the game's story, aesthetics, music, feel, and sensational experience are, without doubt, artistic decisions. All required various calculation modalities, yet the learners were in a constant state of play. If STEM is to truly become STEAM, it should do so through this play pedagogy.

7.6 New Ways of Teaching Art and Design

Recent applications in artificial intelligence that allow computers to compose music, creatively write, and paint on canvas have been received with mixed reviews. While some criticize the authenticity of the computer system's artistic autonomy, others find the produced works of art to be lifeless. Many of us like to hold fast to our understanding that these and all forms of art stem from the human soul, and by harnessing this inner consciousness, all great art is created. I would like to challenge this notion as being only partially true. Indeed, there is something at work in human artistry beyond our current scientific understanding, but there is also a very tangible system of techniques at play that can be quantified and understood as modes of calculation.

British philosopher, C.S. Lewis (1952), elegantly wrote about the different ways of understanding science. We can use the same argument in deciphering the different ways of understanding art and design.

> *In my view the theories are not themselves the things you are asked to accept. Many of you no doubt have read Jeans or Eddington. What they do when they want to explain the atom, or something of that sort, is to give you a description out of which you can make a mental picture. But then they warn you that this picture is not what the scientists actually believe. What the scientists believe is a mathematical formula. The pictures are there only to help you to understand the formula. They are not really true in the way the formula is; they do not give you the real thing but only something more or less like it. They are only meant to help, and if they do not help you can drop them. The thing itself cannot be pictured; it can only be expressed mathematically.* (Lewis, 1952, p. 54-55)

When Lewis uses the term "mathematically" here, he is certainly talking about calculation. He distinguishes two different levels of understanding complex subject matter. On one hand, we can understand something through metaphor and colorful descriptions, but as he points out, this should not be confused with the actual thing you wish to explain. In the case of science and math (and, in Lewis's case, Christianity), they can all be most accurately expressed through formal mathematical descriptions.

We can ask the same question about art and design. How do we understand a work of art? Should we only understand it through the use of metaphor and poetic rhetoric, or can we also understand it through an expression of calculation? This other mode of understanding does not diminish the former; rather, it adds depth to our full understanding of the arts. Lewis points out that, *"A man can eat his dinner without understanding exactly how food nourishes him"* (Lewis, 1952, p. 53). And, likewise, we can surely appreciate any art form without the knowledge of its underpinning design schemas and rules of construction. This, however, does not negate the fact that schemas and rules are there.

Shape grammars used in art analysis help bring this new dimension of understanding to the piece of art. I am not suggesting this is what artists see or do in creating the piece of art under analysis. This is a "way" of looking at it with fresh eyes, through calculation and algorithmic eyes. However, this should not rule out the validity of using such analysis as a precedent for generating new pieces of art. In fact, one could approach painting this way and become very successful doing so.

When I was an undergraduate student at Hampton University in Virginia, I remember taking a humanities course that covered significant African American artists, one of whom was the American painter John Biggers.[29] In that course, we covered all of the cultural significance found in the imagery of his work, but what strikes me today is how little we discussed the visual systems at play in his compositions (I had to come to MIT to do that!). In the case of the Hampton murals, Biggers is explicit in using schemas and iconic forms that he had both used in previous murals and had adopted from his travels in West Africa.

The cultural significance (or artist intent) of the murals *House of Turtle* and *Tree House* have been well documented and were covered in the course. Playful calculation allows us to complement these details to look at the art from the perspective of visual calculation. Many of the murals Biggers painted hold some of the same schemas and mathematical approaches to form creation used repeatedly in a playful manner. *House of Turtle* and *Tree House* are two pieces painted separately but are to be understood as one composition.[30] To achieve this feat, Biggers is forced to devise a schema or underlining design principle that will unify the two pieces yet allow them to be separate compositions in their own right.

---

[29] It is very important that we begin the introduction of John Biggers as an "American" master in contemporary art and not just an "African American" master artist. Too often our achievements are marginalized unfairly by ethno-classifications. The fact that he is a black artist who produces African American art does not diminish the mastery of his craft. It only signifies the genre of his work.

[30] Biggers was commissioned to do the paintings at both Hampton University and Winston-Salem State University at the same time. In all four of the murals, Biggers is explicit in using schemas and iconic forms that he had both used in previous murals and had adopted from his travels in West Africa. Linga, B. A. (1995). As above, so below: John & Jim Biggers' WSSU mural project. *The International Review of African American Art. 12*(4), pp. 42-50. And found in Zeidler, J. (1995). John Biggers' Hampton Murals. *The International Review of African American Art. 12*(4), pp. 51-57.

The significance of a design schema (no matter how formally or informally articulated) is its ability to transfer design knowledge from one composition to another. Many artists do this tacitly over long periods of time. With each painting or sculpture they create, past moves and gestures get carried on to the next. Some artists make these gestures very explicit, while others try to conceal their actions to perpetuate the myth of creative mysticism. I believe it is time to bring into discussion and instruction the algorithmic systems at play in many (if not all) of the art and design we experience and grow to appreciate.

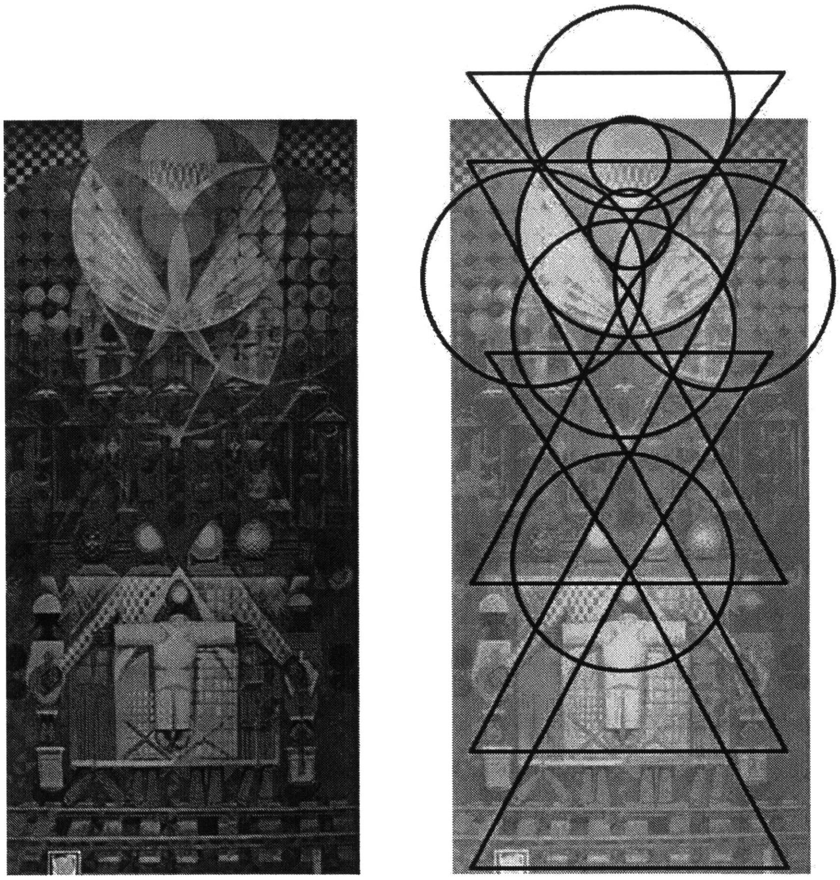

Figure 7.4: John Biggers' mural, "Ascension"

We can find these design schemas in a work of art by creating rules that begin to call forth the shapes seen in the composition. Using our eyes, we can simply pull out the shapes and begin to see how the geometries relate to each other. At first glance, this may sound like some of the art analysis techniques conducted by early 20th-century art educators Denman Ross and Arthur

Dow.[31] They were both fond of the usage of grid overlays to analyze works of art, but it is not clear that their techniques included embedding and explicit shape rules. What William James calls "sagacity" is the same approach playful calculation takes in its ability to pick out the parts we want to see within an entire composition.[32]

Teaching copying is often frowned on by those who hold onto the notion of "originality" being intimately linked with creativity. However, in the work of many great artists (including Biggers), copying is prevalent. They copy from their own work, they copy form other artists, and in some cases they copy from nature. Stiny (2006) observes that being creative is copying. If we are going to teach kids to be creative, we need to show them ways to copy. Copying as a form of play goes all the way back to Caillois's classification of games in which he lists *mimicry*. Although Caillois and others who have looked at mimicry in the play of children are talking mostly about human performance, much can still be learned here in the schema of mimicry play.

7.7 Teaching Creativity with Playful Calculation (Teachers as Play Facilitators)

In the fall of 2014, I taught a special elective at the Harvard Graduate School of Design (GSD) titled, *"Design for Learning."* The course was unique in nature in that it brought together students from the GSD with cross-registered students from the Harvard Graduate School of Education (GSE). The thought behind the course was to dig deeper into the inquiry surrounding the ways in which we teachers can be play facilitators. As a result, "play" itself was a major object of study. Students analyzed their own play as well as the play of others, and the accumulated inquiry resulted in the design of their own playful learning manipulatives.

---

[31] Mine Özkar (2004) presents an extensive look at the techniques used by Ross and Dow in her MIT doctoral thesis—"Uncertainties of Reason: Pragmatist Plurality in Basic Design."

[32] Pawelski, J. O. *The Dynamic Individualism of William James.* Albany, NY: State University of New York, 2007.

The majority of GSD students admitted they had never been exposed to the educational and learning theories that we covered in the course, much of which I have highlighted in this thesis. Secondly, the cross-registered students from the GSE had little experience with design and making, which was another major learning objective of the course. Students from the GSE were constantly being asked to think like designers, and the GSD students were constantly being asked to think like educators. Both were learning how to play!

The final deliverables for the seminar were the design and construction of a playable prototype of a learning game, toy, or manipulative accompanied by a written document outlining how it fits in a specific K-5 curriculum. Partnership with the Boston Children's Museum allowed the participants to develop their projects as students had the opportunity to test their final projects with museum staff, parents, and children visitors. The written component of the final projects took the form of an educator's curriculum guide. It answered questions about how the object or game fits into a larger learning objective for the players. Instructions for playing with the designed manipulative highlighted some examples of play and use.

Figure 7.5: GSD Design for Learning final exhibit at Boston Children's Museum

(Photo © Harvard GSD/Maggie Janik)

There were several great takeaways for all of the participants of this class. From an educator's point of view, this highlighted that teachers could not only play the role of play facilitator, but they could become makers to create original games of their own. The educators also discovered the benefits of placing open-ended game activities in their curriculum to allow their own students to tweak and modify the game to their own purposes. There has been much talk about the need to have "maker spaces" in K-12 educational environments, but the majority of this discussion is focused on the students' use of the space and how they learn in them. This seminar highlighted the need for teachers to inhabit these spaces as well, to create games and learn manipulatives of their own so as to fully become creative play facilitators. Teachers would no longer be restricted to off-the-shelf products but could invent their own playful teaching tools and games.

From the design student's point of view, the class was equally successful. Thinking about thinking is the type of "metacurricular" activity we want any great learner to partake in (Schwartz & Perkins, 1997). The GSD students found the process of creating objects of play very insightful for their own design process. In order for them to go through the process of creating playful learning objects, they had to analyze the proposed play through their own "play grammars." The students created schemas to articulate all of the components of their play before they were even manifested in physical form. When they did create the prototypes, they were then able to use these formal expressions to analyze what they had created. All of the final projects were successful, and many involved components that allowed children to build their visual calculation skills through spatial/sensory exploration.

7.8 Teaching Technology with Playful Calculation

Certain technologies are bringing back to the forefront the element of play in how we perceive and design space. The *Oculus Rift*, for instance, is a tool that is not just changing design visualization but could also change the overall design process. Anyone who has had the "Oculus experience" knows that this is much more immersive than 3D stereoscopic viewing or other virtual reality predecessors. Howard Burns (famed architecture historian), after viewing a computer model of Palazzo Chiericati through the *Oculus Rift,* exclaimed, *"We don't need to go to Vicenza anymore. We have it right here!"* True enough, the *Oculus Rift* gives the viewer the closest experience to being "in" a space without physically being there, but this is only the tipping point.

Figure 7.6: Using the *Oculus Rift* to perform design tasks

In a recent research initiative at MIT, we looked at the feasibility of a fully immersive design environment. We wanted to move beyond using the *Oculus Rift* for project visualization and see if we could actually perform design tasks within the VR space at a 1:1 scale. [33] The end product, I must admit, was clunky (as most prototypes are), but it worked! We used the *Oculus Rift,* Microsoft Kinect, a hacked Wii Fit board, and programmed the entire experiment in Unity. We experimented with the "kit of part exercise," a problem set given to most architecture students in their first year of study (Ockman et al., 2012). Instead of fiddling around with physical wooden scale models through our system designers, we were able to walk around a VR world and move the full scale kit of part components with our arms and hands. We can design and construct almost as a child would in building a play fort.

The use of the child metaphor is intentional to highlight the fact that "play" is essential to learning (Dewey, 1938; Paley, 2004; Thomas & Brown, 2011). In spite of its importance, the element of play seems to decrease the higher we move up in education, and design education

---

[33] The *Oculus Rift* is a virtual reality (VR) headset developed by the Oculus Company. Traditionally, the hardware is developed for the use of gaming and entertainment.

is not immune to this. The 2001 AIAS Studio Culture Task Force wrote a comprehensive report on the various ills of studio culture (Dutton, Koch, Schwennsen, & Smith, 2002). Students often experience high levels of stress and frustration from lack of clarity, and carry a gloomy sense of defeat (Casakin & Shulamith, 2008). This is not the description of a playful environment. Stuart Brown (2009) reminds us that, *"It energizes us and enlivens us. It eases our burdens. It renews our natural sense of optimism and opens us up to new possibilities"* (p. 4). There is a disconnect in our educational experiences. We begin our educational journey in kindergarten, where learning is all about play, but as we progress through grade levels, something happens. By the time you find yourself in architecture school, playing to learn is a vague memory.

The absence of play became even clearer when I observed my own students for the first few days of a graduate seminar I taught called *Rule-Based 3D Modeling: Learning Through Play.* For every class, I used one of the three hours and called it "Play Time." On different days, students were given play objects (from toys to video games) in which they were guided through the cycle of playing, reflection, and discussion. The first day, they were presented with ping pong balls, plastic cups, string, paper, and wooden dowels; they looked at me with great confusion when I gave the simple instruction to take these and play for 15 minutes. In contrast, my toddler daughter and son would have no problem with this assignment. The problem would only exist if I pulled out those materials and said NOT to play with the things or simply asked them to share the materials with each other. Yet, for these bright graduate students, there was a moment of hesitation, nervous laughter, and puzzled looks begging for more instruction. Throughout the semester, students eventually loosened up and began to delight in that hour of play. The semester ended with students "playing" their final projects. Students created their own unique computer modeling applet.

This seminar was trying to push the envelope on design education and bring us back to a place where play is central to learning. At the same time, emerging technologies like the *Oculus Rift* are presenting new playful ways to approach design. In each of these cases, designers and educators will need to learn a new set of skills to play in this metaphorical playground. They will need to learn new ways to calculate; without this skill, they will not gain access to the playground. In using the term "calculate," I am not only referring to mathematics, nor am I limiting this term to the use of computer languages (Java, C++, C#, Python, and MATLAB to name a few). Calculation is inclusive of these things but can also extend beyond the digital back into the domain of tangible objects. Designers should willingly embrace the multiple forms of calculation.

For a long time, architects have held onto “sketching” as the primary skill that gave them creative superiority over other professions (Allsopp, 1952; Lawson, 1990; Lawson, 2004). This was our main “super power,” so to speak, in keeping authority over several aspects of the design process. While sketching is not going away, sketching skills alone will not save architecture and design from the coming age, where design professionals are not just “users” of new technology but hackers and creators of new technology themselves. Sketching is one particular way we calculate with our eyes, but there are other intuitive and algorithmic ways of thinking.

This extended perspective of calculation has a lot to do with what I have been passionate about in researching the changing face of K-12 STEM education. Beyond project-based learning and beyond the STEM to STEAM movement, there is a hidden element found in design education that could help build the skills necessary to be both visually artistic and analytically systematic (Stiny, 2006). Playful calculation is a way to bridge the gap between these different modalities of thinking. We can use rules and algorithms along with intuition to be artistically creative. To further this pedagogy, I have documented what happens when children play and have begun translating these observations into ideas on how we can build algorithmic thinking into foundational art and design studies.

Many teachers ask how we can integrate technology into K-12 arts education; this research suggests we pay more attention to how the arts can be used to better understand and develop new digital tools and devices. An example of such new tools can be seen in the growing increase of plugins for off-the-shelf 2D and 3D software. A plugin is pseudo software created to work in harmony with an existing software program. *Grasshopper,* for instance, is a visual programming tool created to work with *Rhino*, a popular 3D modeling software. *Grasshopper* allows 3D artists to parametrically create digital sculptures. Tools like these are created by individuals who are trying to extend the usage of software beyond its current configuration. This would not be made possible without some foundational understanding of computer programming.

While some are weary that technology and software provide amateur artists a one-click solution to produce pieces of art, playful calculation relies on the human eye to mindfully guide the design process. Advances in technology will never tell you why you should use any particular rule, what rules to use, or even in what sequence to use them in. Algorithmic thinking in the arts does present a way to calculate, a way to create art and talk about art, and a way to think reflectively about what you are doing for inspiration to move forward.

Artists and art educators who choose to adopt new technologies in their practice will be forever at the mercy of the computer scientists unless they take it on themselves to become technology creators and not just tech-users. The transition between being a consumer of technology to becoming a creator of new technology can be a long and difficult journey for many. However, if we introduce computer science concepts to children at the same time we are building foundational understanding in the arts, we may be able to produce a generation of artfully minded technologists or techno-minded artists. A prerequisite to becoming a great computer coder is the ability to think algorithmically. Prior to learning a programming language or soldering hardware, the individual must have an ability to see and think in systems. Playful calculation is a formal method to build foundational algorithmic thinking skills. By teaching students how to create rules and schemas that algorithmically generate works of art, we are providing a more flexible and intuitive entry point to integrate technology into art education.

Most instructors of computer programming would agree that there are broad concepts that must be understood by students in order for them to learn any coding language. System and algorithmic thinking are two terms found in new curricula to teach students coding. An algorithm is nothing more than a recipe or set of instructions, but young students rarely approach problem solving of any sort by writing out a procedure. Visual arts naturally lend themselves as a way to get students to think about procedural methods.

System thinking is critical in understanding the various components that must come together to complete a proper executable computer code. With terms such as objects, classes, variables, and packages, it is often difficult for students of any age to grasp what this all means. Beyond their meanings (and arguably more significant) is the relationships these things have with each other. When students get a clear grasp on the organization of the system, they can easily transfer the knowledge of one programming language to another.

In recent years, there has been a big push to teach children computer programming at a young age. Creative software like *Scratch* from the MIT Media Lab's Lifelong Kindergarten Group has helped thousands of children partake in inquisitive play in the world of computer programming. They do this by simplifying many of the components needed to write a program and present them in simple intuitive interfaces (Ford, 2009). Within a few hours, children are able to make little applets, games, and a wide range of creative projects.

In many ways, the play within *Scratch* is combinatorial play. The interface not only borrows from *Lego* but visually has strong similarities. As pointed out earlier, combinatorial play is often a great starting point for young learners but should not be seen as the end-all. Even within the realm of coding, there can be several in-between moments that are wonderful and should be explored. If artists only limit themselves to seeing variables as 0-dimensional units, then they will miss opportunities to see the emergence of new components.

In object-oriented programming, statements that have a set of parameters attached to them are called conditional statements. The same occurs in mathematics and is fundamental to both rule creation and algorithmic thinking. “If-then” and “if-then-else” are both used to increase the complexity of simple rules, making them much more robust. Visual calculation constantly operates under the same type of logic. When children observe the spatial relationship of shape variables, their configuration communicates to them the emergent shape. The “if” statement is played out in the cause and effect observed by the eye during play actions.

Chapter 8

Conclusion

8.1 The Unsegregated STEM Curriculum

The construct of knowledge that is pervasive across all disciplines is in its relationship with design. To quote David Perkins (1986), *"Knowledge is design."* Our most common way of understanding the various subjects in school is under the position that knowledge is simply information. We teach as if each subject contains a unique body of information specific to the discipline being taught. In math, we pass on information on mathematics to students; in science, we need to pass the information of science on to students, and so forth. Understanding knowledge as information that needs to be passed from one individual to another is only one way of understanding knowledge. A much more generous way to think about knowledge is in the way it is used. Knowledge can be understood as having a unique structure adapted for a purpose (or purposes). Knowledge is, therefore, a tool.

Perkins (1986) notes that this perspective of knowledge as design can be tested across four guiding questions:

1) What is the purpose (purposes)?
2) What is its structure?
3) What are model cases of it?
4) What are arguments that explain and evaluate it?

The evaluative question of the "purpose of knowledge" in the arts can lead to many open-ended answers. Art can have the purpose to evoke emotions or communicate ideas from the mind of the artist. In industrial design, engineering, and architecture, the answer can be much more straightforward, but what of subjects such as mathematics, history, and literature? Knowledge in these subject areas can also go under the scrutiny of articulating the purpose question. When we position the information in the context of a purpose usable to the learner, we transition from a passive type of knowledge to that of an active knowledge that is more creative.

Looking at the structure of a body of knowledge is an exercise of analysis that cuts across all disciplines. If we cannot articulate the structure of something, then how can we really understand it? This is the art of proper analysis. The structure of a poem, a mathematical equation, or a historical fact can all be broken down to its constituent components. Perkins' model of structural analysis of knowledge stops at combinatorial decomposition, but Stiny's model of calculation allows us to go beyond this model into a dynamic analysis that includes embedding.

Probing the question, *"What are the model cases of knowledge?"* allows us to further use calculation techniques found in shape grammars. In knowledge as design, models are examples and forms of representations that "make the concept more accessible by rendering it concrete, perceptual and vivid." In most cases the model used is the model of the structure of another source. So we can use the same techniques of knowledge structure analysis as previously described in presenting model examples of knowledge.

In architectural design, this is called the use of precedent. Perkins (1986) gives elaborate definitions for the usage of maps, graphs, and mathematical functions all as examples of the abstract ways in which models can take. As he states, *"Equations themselves do not display the way objects move, but rather offer formulae characterizing their motions"* (p. 129). He further mentions the creation of mental models as a method to store models for further use. While mental models can be helpful for quick access to compare bodies of knowledge, they can also prevent pitfalls in the way they can take over the mind and lock the individual into one way of thinking. This can be avoided by the translation of mental models onto paper using descriptive rules, and schemas, all with the expanded view of embedding.

Knowledge as design as opposed to knowledge as information is a much more expanded view that allows us to desegregate subjects taught in school. We can look at any body of knowledge and probe it with the four questions, all while using playful calculation to expand the way in which we look at the structure of the knowledge and the way in which we present models of it. As Perkins writes,

> *The usual subject matters need not stand so distant from one another. In fact, it might be said that they only stay so because they are left there. Instruction based on knowledge as design need not, indeed should not, accept this status quo. Knowledge as design is a natural bridge builder, pointing up commonalities and inviting contrasts between various disciplines.* (Perkins, 1986, p. 222)

8.2 Playful Calculation and Common Core Standards

Traditionally, each US state designs its own set of standards for student achievement in K-12 mathematics, language arts, and science, but in recent years, a program called the "Common Core Standards" has been offered to consolidate the standards into one system that is the same across the entire country.[34] The cause behind this is the noticeable inconsistency in what each state calls "high achievement" in these subject areas, a revelation that often shows up when students are competing for spots in highly sought-after universities. What Common Core claims to do is "level the playing field."

The program has been received with mixed reviews and has not been fully adopted by all US states. Supporters of the system believe that it is a great foundation to address school inequality. They see Common Core Standards not in a restraining way but as a framework where students can still develop their own individual approach to learning the subject matter. The Common Core sets universal goals across the nation for all students in a grade level, but it does not necessarily dictate the exact route to reach these goals. The flexibility here is what most supporters (teachers and parents) try to highlight.

Those that are critical of this system are not so convinced of this flexibility. Because assessment is such a strong part of the Common Core, critics see examples of teachers organizing their entire curriculum around the "testing" components of it. Teachers are teaching for the test. Equally, students are aware of the assessment test and face these tasks with great anxiety. The result of this educational system yields teaching methods that revert to drilling students to memorize information through repetition. While most educators would agree that this behaviorist model of learning is ineffective long-term for the students, they also see the direct pressure of achieving scores in class assessment test.

---

[34] Common Core Standards are currently adopted by 44 of the 50 states in the US. The Common Core Standards formulize achievement marks for each age group in the subjects of math and science. To date, this concept is still held as a contentious topic in local and state politics.

"Critical thinking skills" is a buzz term that the Common Core Standards claim to promote. They encourage the idea that, for student learning, it is not only about getting the right answers but also about emphasizing how students reach appropriate solutions. They want students to develop both reasoning skills and creativity. Curricula that do this best use "project-based learning" as a means to achieve these goals. By placing students in a context that allows them to apply things they have learned, critical thinking, processing concepts for solutions, and creative inquiry can all be developed.

Under Common Core Standards, the project-based learning approach has proven to be the best model to execute all of the virtues it wishes to promote, and it is here where playful calculation can be most effective in extending the learning goals. Project-based learning treats knowledge as design, allowing for the same playful calculation techniques that we find in design and the arts. Project-based learning also expands the subject inquiry to include aesthetics, a cornerstone of delight inquiry. To say the least, Common Core Standards could greatly improve by adopting play pedagogies.

8.3 Future Directions

In the future, I would like to spend further time investigating the *Shape Game* and other variations of it on a digital platform. Early studies of this were investigated using the *Unity 3D Game Engine,* and the results were most promising. There were several new discoveries I could see that this method of play could offer to the inquiry into spatial thinking and visual calculation.

In general, computer games harness computational power to give the *Shape Game* capabilities the non-computer games do not have. This can easily be observed in the difference *Tetris* has as opposed to physical sorting puzzles of the same game mechanics. Digital games have a seductive way in which the games engage learners through stimulating the senses (Gee, 2007; Schell, 2008). The computational power, on the back end of video games, powers them with great speed and graphic clarity using an array of sensory stimuli to keep the player engaged. The computer game version of the *Shape Game* would be able to give feedback to the user for success and failure, keep a memory for progress and achievements, and enable the player to share certain tasks with the artificial intelligence of the game itself. The computer game would include sounds, more colors, as well as bring to the forefront the scoring component.

Another advantage of mirroring the *Shape Game* in a digital platform would be the way I could then scaffold in the various levels of difficulty in solving the pattern cards. Video games have the ability to be adaptive to the user. Instead of the "one size fits all" model of learning, good video games adapt to the user (Gee, 207; Schell, 2008). The *Shape Game* as a computer game would then scaffold the learning experience in the game itself. Most players do not bother with reading full-length manuals prior to game play. They simply jump into the experience and learn through playing. Good games are designed to allow players to learn the game by controlling the task and level of difficulty within the early moments of play, thus allowing players to begin to construct their own knowledge of how to go about playing. Good computer games are constructivist-based in nature.

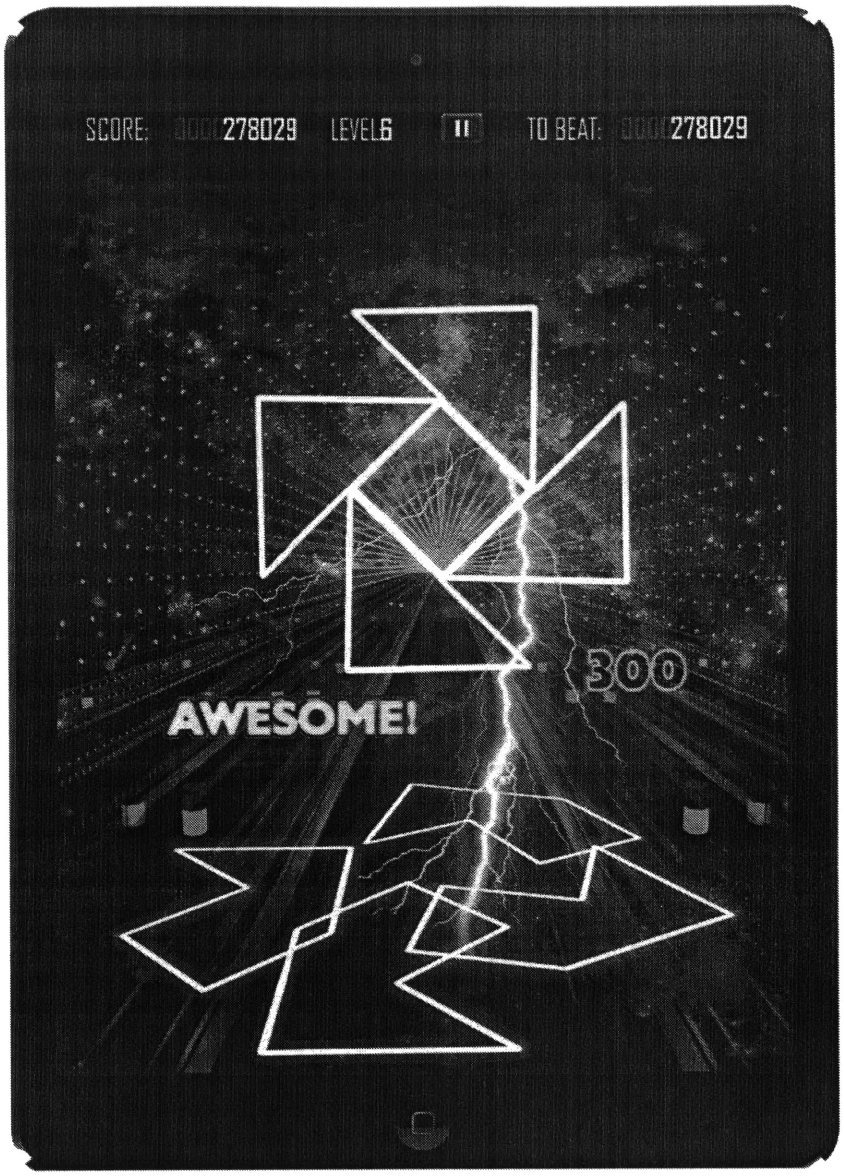

Figure 8.1: Shape Game mobile game concept

Finally, the *Shape Game* as a video game would further facilitate group play and learning. Imagine if we had *"Words with Friends"* being played with shapes and shape compositions! The computational affordances of bringing several people together to complete a common task are many. Here the magic circle is fully personified as players create their own shape patterns to be solved and share them in a larger playing environment. The digital platform would allow us to embed a screen-saver mechanic that allows players to take snapshots of their compositions as they play with the shape pieces in free play mode.

8.4 Final Reflection

There are a few major contributions this research has accomplished:

1) Shape grammars that had never been tested in K-12 learning environments were tested in the same.
2) Play and games that have never been studied from the aspect of visual calculation using rules and schemas to understand their unique structure were studied in the same.
3) A strong argument for calculation and embedding to serve as a conceptual model for approaching learning and knowledge acquisition were presented.
4) The *Shape Game,* a unique product, allowed players to strengthen algorithmic thinking and visual calculation skills.

Like any other major theoretical position on education or computing, the ultimate proof of its significance will come in its adaptation in use. I will try my hardest to be optimistic, even with the knowledge of how hard it is to shift education paradigms. The critique and suggestions on design education (and education at large) share roots that are over 30 years old, and even within the field of shape grammar, there is much pioneering still to be done for educators to widely adopt its use. I can feel some measure of success and satisfaction if a simple game can help promote the playful nature of calculation. If anything, I hope readers will all take a close evaluation of their daily practices to insure they have not forgotten to play.

Bibliography

Ackermann, E. (1994). Construction and transference of meaning through form. In L. P. Steffe & J. Gale (Eds.), *Constructivism in education* (pp. 341-354). Mahwah, NJ: Lawrence Erlbaum Associates, Inc., Publishers.

Ackermann, E. (1996). Perspective-taking and object construction: Two keys to learning. In Y. Kafai & M. Resnick (Eds.), *Constructionism in practice: Designing, thinking, and learning in a digital world* (pp. 25-37). Mahwah, NJ: Lawrence Erlbaum Associates, Inc., Publishers.

Alexander, C. (1964). *Notes on the synthesis of form.* Cambridge, MA: Harvard University Press.

Allsopp, B. (1952). *Art and the nature of architecture.* London, England: Sir Isaac Pitman & Sons.

Argyris, C., & Schön, D. A. (1974). *Theory in practice: Increasing professional effectiveness.* San Francisco, CA: Jossey-Bass, Inc., Publishers.

Atkinson, P., & Delamont, S. (2006). *Narrative methods* (Vol. 1, p. xxi). London, England: SAGE Publications.

Birkhoff, G. D. (1933). *Aesthetic measure.* Cambridge, MA: Harvard University Press.

Bloom, H. (1973). *The anxiety of influence: A theory of poetry.* New York, NY: Oxford University Press, Inc.

Brown, S. (2009). *Play: How it shapes the brain, opens the imagination, and invigorates the soul.* New York, NY: Penguin Group.

Butterworth, B. (2003). The development of arithmetical abilities. *Journal of Child Psychology and Psychiatry, 46*(1), 3-18.

Butterworth, T. (1990). Detroit string quartet. In J. R. Hackman (Ed.), *Groups that work (and those that don't): Creating conditions for effective teamwork* (pp. 207-224). San Francisco, CA: Jossey-Bass, Inc., Publishers.

Caillois, R. (1961). *Man, play, and games.* New York, NY: The Free Press of Glencoe.

Casakin, H., & Kreitler, S. (2008). Correspondences and divergences between teachers and students in the evaluation of design creativity in the design studio." *Environment and Planning B: Planning and Design, 35*(4), 666-78.

Chapin, F. (1894). *Freidrich Froebel yearbook.* Chicago, IL: Kindergarten Literature Co.

Cross, J. (2007). *Informal learning: Rediscovering the natural pathways that inspire innovation and performance.* San Francisco, CA: Pfeiffer.

Csikszentmihalyi, M. (1990). *Flow: The psychology of optimal experience.* New York, NY: Harper & Row.

Davies, C. A. (1998). *Reflexive ethnography: A guide to researching selves and others.* Abingdon, Oxon, England: Routledge.

Dewey, J. (1929). My pedagogic creed. *Journal of the National Education Association, 18*(9), 291-95.

Dewey, J. (1938). *Experience and education.* New York, NY: Kappa Delta Pi.

DuFour, R. (2003). Building a professional learning community: For system leaders, it means allowing autonomy within defined parameter. *School Administrator, 60*(5), 13-18.

Dutton, T., Koch, A., Schwennsen, K., & Smith, D. (2002, December). *The redesign of studio culture: A report of the AIAS studio culture task force.* Retrieved from http://www.aias.org/wp-content/uploads/2014/06/314.pdf

Eisner, E. W. (2002). *The arts and the creation of mind.* New Haven, CT: Yale University Press.

Emerson, R. M., Fretz, R. I., & Shaw, L. L. (2011). *Writing ethnographic fieldnotes.* Chicago, IL: The University of Chicago Press.

Faste, R. A. (1995). The role of aesthetics in engineering. *Japan Society of Mechanical Engineers (JSME) Journal*, Winter.

Fisher, T. (2000). *In the scheme of things: Alternative thinking on the practice of architecture.* Minneapolis, MN: University of Minnesota.

Ford, J. L. (2009). *Scratch programming for teens.* Boston, MA: Course Technology.

Froebel, F. (1887). *The education of man.* (W. N. Hailmann, Trans.) New York, NY: Appleton. (Original work published 1826)

Futschek, G. (2006). Algorithmic thinking: The key for understanding computer science. In R.T. Mittermeir (Ed.): *Informatics education – The bridge between using and understanding computers* (pp. 159-168). Heidelberg, Germany: Springer.

Gardner, H. (1983). *Frames of mind: The theory of multiple intelligences.* New York, NY: Basic Books.

Gardner, H. (1991). *The unschooled mind: How children think and how schools should teach.* New York, NY: Basic Books.

Gee, J. P. (2003). *What video games have to teach us about learning and literacy.* New York, NY: Palgrave Macmillan.

Goethe, J. W. Von. (1906). *The maxims and reflections of Goethe.* (B. Saunders, Trans). New York, NY: The Macmillan Company. (Original work published in 1892)

Habraken, N. J., Gross, M. et al. (1987). *Concept design games. Book one: Developing.* Cambridge, MA: Massachusetts Institute of Technology.

Habraken, N. J., Gross, M. et al. (1987). *Concept design games. Book two: Playing.* Cambridge, MA: Massachusetts Institute of Technology.

Hackman, J. R. (2002). A real team. In J. R. Hackman (Ed.), *Leading teams: Setting the stage for great performances* (pp. 37-60). Boston, MA: Harvard Business School Press.

Hartman, C. (1996). *The virtual muse: Experiments in computer poetry*, Hanover, NH: Wesleyan University Press.

Hegel, G. W. F. (1975). *Hegel's aesthetics: Lectures on fine art.* (T. M. Knox, Trans.) Oxford, England: Clarendon. (Original work published 1835).

Hetland, L. (2007). *Studio thinking: The real benefits of visual arts education.* New York, NY: Teachers College.

Hoffmann, A. (1893). *Puzzles old and new.* London, England: Frederick Warne.

Huizinga, J. (1955). *Homo ludens: A study of the play-element in culture.* Boston, MA: The Beacon Press.

Jackson, J. (2004). An ethnographic filmflam: Giving gifts, doing research, and videotaping the native subject/object. *American Anthropologist, 106*(1), 32-42.

Krechevsky, M., Mardell, B., Rivard, M., & Wilson, D. (2013). *Visible Learners: Promoting Reggio-Inspired Approaches to Schools.* San Francisco, CA: Jossey-Bass.

Knight, T., & Stiny, G. (2001). Classical and non-classical computation. *Arq: Architectural Research Quarterly 5*(04), 355-372.

Knight, T. (2003). Computing with emergence. *Environment and Planning B: Planning and Design 30*, 125-55.

Knight, T. (2012). Slow computing: Teaching generative design with shape grammars. *Computational Design Methods and Technologies: Applications in CAD, CAM and CAE Education.* IGI Global, 34-55. Web. 27 Aug. 2014.

Knight, T. W. (1994). *Transformations in design: A formal approach to stylistic change and innovation in the visual arts.* Cambridge, England: Cambridge University Press.

Kohn, A. (1986). *No contest: The case against competition.* Boston, MA: Houghton Mifflin.

Kudrowitz, B., & Wallace, D. (2010). The play pyramid: A play classification and ideation tool for toy design. *The Journal of Arts and Technology, 3*(1), 36-56.

Langer, E. J. (1997). *The power of mindful learning.* Reading, MA: Addison-Wesley.

Lawson, B. (1990). *How designers think.* London, England: Butterworth Architecture.

Lawson, B. (2004). *What designers know.* Oxford, England: Elsevier.

Lewis, C. S. (1958). *Mere Christianity.* New York, NY: Macmillan.

Love, T. (2003). Kit-of-parts conceptualism. *Harvard Design Magazine, 19,* 40-47.

Mitchell, W. J., & McCullough, M. (1995). *Digital design media.* New York, NY: Van Nostrand Reinhold.

Necker, L.A. (1832). Observations on some remarkable optical phaenomena seen in Switzerland; and on an optical phaenomenon which occurs on viewing a figure of a crystal or geometrical solid. *London and Edinburgh Philosophical Magazine and Journal of Science, 1*(5), 329–337.

Newton, D. P. (2000). *Teaching for understanding: What it is and how to do it.* London, England: Routledge/Falmer.

Ockman, J., & Williamson, R. (2012). *Architecture School: Three Centuries of Educating Architects in North America.* Cambridge, MA: Massachusetts Institute of Technology.

Paley, G. V. (2004). *A child's work: The importance of fantasy play.* Chicago, IL: University of Chicago Press.

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas.* New York, NY: Basic.

Perkins, D. N. (1981). *The mind's best work.* Cambridge, MA: Harvard University Press.

Perkins, D. N. (1986). *Knowledge as design.* Hillsdale, NJ: Lawrence Erlbaum Associates, Inc., Publishers.

Perkins, D. N. (1995). *Software goes to school: Teaching for understanding with new technologies.* New York, NY: Oxford University Press.

Piaget, J., Inhelder, B., Alina, S., & Lunzer, E. A. (1960). *The child's conception of geometry.* London, England: Routledge and Paul.

Sorensen, E. K. (2004). Reflection and intellectual amplification in online communities of collaborative learning. In T. Roberts (Ed.) *Chapter XI: Online collaborative learning: Theory and practice* (pp. 242-261). Hershey, PA: Idea Group Publishing.

Roblyer, M.D., & Doering, A. H. (2010). Theory and practice, foundations for effective technology integration. In *Integrating Educational Technology into Teaching* (5th Ed., pp. 32-70). Boston, MA: Allyn & Bacon.

Ruskin, J., & Sturgis, R. (1899). *The seven lamps of architecture: Architecture and painting by John Ruskin.* New York, NY: D. Appleton.

Salen, K., & Zimmerman, E. (2003). *Rules of play: Game design fundamentals.* Cambridge, MA: Massachusetts Institute of Technology.

Salimpoor, V. N., Benovoy, M., Larcher, K., Dagher, A., & Zatorre, R. J. (2011). Anatomically distinct dopamine release during anticipation and experience of peak emotion to music. *Nature Neuroscience 14*(2): 257-262. Web.

Schell, J. (2008). *The art of game design: A book of lenses.* Amsterdam, Germany: Elsevier/Morgan Kaufmann.

Schmuck, R. A., & Schmuck, P.A. (1971). *Group processes in the classroom.* Dubuque, IA: W.C. Brown.

Schön, D. A. (1983). *The reflective practitioner: How professionals think in action.* New York, NY: Basic Books.

Schön, D. A. (1987). *Educating the reflective practitioner: Toward a new design for teaching and learning in the professions.* San Francisco, CA: Jossey-Bass, Inc., Publishers.

Shih, S., Hu, T., & Chen, C. (2006). A game theory-based approach to the analysis of cooperative learning in design studios. *Design Studies, 27*(6): 711-722.

Singer, I. (2011). *Modes of creativity.* Cambridge, MA: Massachusetts Institute of Technology.

Singer, D. G., & Revenson, T. A.(1997). *A Piaget primer: How a child thinks.* Madison, CT: International Universities.

Slocum, J., & Botermans, J. (1986). *Puzzles old and new: How to make and solve them.* Seattle, WA: University of Washington.

Smith, D., & Goldhaber, J. (2004). Collaborating with clay and each other. In D. Smith & J. Goldhaber (Eds.), *Poking, pinching & pretending* (pp. 45-56). St. Paul, MN: Red Leaf Press.

Stiny, G., & Gips, J. (1972). Shape grammars and the generative specification. In O.R. Petrocelli (Ed.), *Best computer papers of 1971* (pp. 125-135). Boca Raton, FL: Auerbach Publications.

Stiny, G., & Gips, J. (1978). *Algorithmic Aesthetics: Computer Models for Criticism and Design in the Arts.* Berkeley, CA: University of California.

Stiny, G. (1980). Kindergarten grammars: Designing with Froebel's building gifts. *Environment and Planning B: Planning and Design, 7*(4), 409-462.

Stiny, G. (2006). *Shape: Talking about seeing and doing.* Cambridge, MA: Massachusetts Institute of Technology.

Stiny, G. (2010). What rule(s) should I use? Paper presented at Nexus 2010: Relationships Between Architecture and Mathematics, Porto, Portugal. 13-15.

Thomas, D., & Brown, J. S. (2011). *A new culture of learning: Cultivating the imagination for a world of constant change.* Create space Independent Publishing Platform.

Webb, N. M., & Palincsar, A. S. (1996). Group processes in the classroom. In D. Berliner & R. Calfee (Eds.), *Handbook of educational psychology* (3rd ed., pp. 841-873). New York, NY: Macmillan.

Wiggin, K. D. S., & Smith, N. A. (1895). *Froebel's gifts.* Boston, MA: Houghton Mifflin.

Vygotskiĭ, L. S., & Cole, M. (1978). *Mind in society: The development of higher psychological processes.* Cambridge, MA: Harvard University Press.