ETHNOCOMPUTATION
On Weaving Grammars for Architectural Design

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Abstract

The aesthetic, structural, and functional aspects of weaving are parallel to the ideal Vitruvian model of an architecture that expresses an inclusive aesthetic, resonating from the logic of the design, structure and construction process. However, despite the strong historical connection between weaving and architecture at their earliest inception, the ideal model of weaving does not fully translate into most of today's architecture.

In a quest to reinvent architectural weaving, the conception of weaving is challenged, reconfigured, and reformulated through *in situ* observation and computational design formulation. This dissertation proposes methodologies to interpret tacit knowledge in traditional weaving through an EthnoComputation lens and to reinvent architectural weaving with two Weaving Grammars.

Thesis Supervisor: Terry W. Knight
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To Anevay and Ryuzen

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1 INTRODUCTION

The aesthetic, structural, and computational aspects of weaving exemplify the ideal Vitruvian model of an architecture that expresses an inclusive aesthetic, resonating from the logic of the design and the construction process.

Weaving and architecture were strongly connected at their earliest inception. However, despite this strong historical connection, the ideal model of weaving has not been fully translated into today's architecture. The application of weaving in architecture will be referred to here as *architectural weaving*. In today's architecture, the structure-aesthetic relation in architectural weaving remains fragmented. Moreover, the progress of architectural design inspired by weaving is far behind the evolution of weaving in traditional settings.

This dissertation proposes methodologies with which to interpret tacit knowledge in traditional weaving through a computational lens and to reinvent architectural weaving with hybridized schemas from both a traditional environment and computational principles. In a quest to reinvent architectural weaving, the conception of weaving is challenged, reconfigured, and repositioned through *in situ* observation and computational design formulation.

1.1 Background

Weaving has been coevolving with human civilization, from the production of early survival tools, such as shelter and clothing, to the automation of weaving in the Jacquard loom. As the terms 'technology' and 'textile' are both derived from the Latin word *texere*, which means 'to weave', 'to connect' and 'to construct', the use of weaving can be traced back to the origins of textiles and architecture.[1] [2] Gottfried Semper, in *The Four Elements in Architecture,* states that the origin of architecture overlapped with the creation of textiles at the time when humans

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[1] John Gillow and Bryan Sentance, *World Textiles: A Visual Guide to Traditional Techniques* (Thames & Hudson, 2005).
[2] Henry Barker, *Egyptian Gods & Goddesses* (Grosset & Dunlap, 1999).

invented the interwoven fence as the earliest partition for an enclosure.[3] This then led to the invention of other woven objects for domestic household purposes. Frei Otto makes a corresponding argument that early humankind's first dwelling was woven with flexible and vegetal materials (young conifer, bamboo, or branches of broad-leaved trees) because these materials are easily harvested and manipulated with bare hands.[4] Today, the legacy of weaving with flexible vegetal material can still be found in many traditional crafts and traditional house constructions. In some cultures, weaving is frequently used for wall-partitions, sometimes with ornament that is applied in the textile's woven pattern, to decorate the house.[5] [6] [7]

Rational Weaving

In addition to the role of weaving in architecture and craft, the logical aspect of weaving has allowed it to travel across disciplines. The rationality of weaving is construed from its discrete and continuous property. On one hand, the checkered pattern from the over-and-under configuration appears as an assemblage of pixels that is countable in the interwoven surface. On the other hand, the continuous material (i.e., thread) allows for the depiction of a continuous line or plane made by one thread as it passes over or under other threads.

The association of continuous material and discrete pixilation makes the technique of weaving popular and effective in forming images or patterns in textiles. It is this pixilation pattern that allow weaving to be converted into a computable element. The Jacquard Loom machine, demonstrated by Joseph-Marie Jacquard in 1801, became one of the most celebrated milestones in computer science. Jacquard substituted for the weaver's role in handling the warp and weft by using holes in a punched card as the pattern-keeper that instructed the weft to go over or under the warp when looming the patterns.[8] [9] The Jacquard

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[3] Gottfried Semper, *The Four Elements of Architecture and Other Writings*, Reissue (Cambridge University Press, 1851).
[4] Frei Otto, *IL-37 Ancient Architects* (Universität Stuttgart, 1994).
[5] Miriama Evans, *The Art of Māori Weaving: The Eternal Thread* (Wellington N.Z.: Huia Publishers, 2005).
[6] Martin Prechtel and Robert S. Carlsen, "Weaving and Cosmos Amongst the Tzutujil Maya of Guatemala," *RES: Anthropology and Aesthetics*, no. 15 (April 1, 1988): 122–32.
[7] Kate P. Kent, "West African Decorative Weaving," *African Arts* 6, no. 1 (October 1, 1972): 22–88, doi:10.2307/3334637.
[8] T. F. Bell, *Jacquard Weaving and Designing* (Longmans, Green, 1895).

loom started the era of automation, and many computational pioneers began working with punched cards. Charles Babbage adapted the punched card mechanism for his Difference Engine and Analytical Engine designs in 1820, and in 1845 Herman Hollerith embedded census data into the pattern of holes used for his tabulator machine. Using Hollerith's mechanism, IBM tabulation machinery was developed, and IBM's card reader and cardpunch machine assisted the birth of ENIAC, setting off the digital era in computer science.[10]

Today, decades after punched cards have been replaced by circuit boards, the computational aspects of weaving remain ubiquitous in multidisciplinary fields.[11] Experts in electronics and biotechnology make broad use of weaving principles, including identifying proteins using knot-theory, knitting articulate cartilage in tissue engineering and knotting conductive thread into circuit boards.[12] [13] [14] [15] In mathematics, the formal expression of numerical weaving has been formulated in algebra, arithmetic and trigonometry equations — namely, in knot theory, braid theory and topology.[16] [17]

"Educultural" Weaving

As part of everyday craft activity, weaving has been passed down through generations with various purposes in different cultural contexts. In Zinacantan, Mexico, for instance, cultural customs exist that lead to improved weaving ability. As observed by Patricia Greenfield, Zinacantec infants are trained to be natural

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[9] James Essinger, *Jacquard's Web: How a Hand-Loom Led to the Birth of the Information Age* (Oxford: Oxford University Press, 2004).
[10] Norman Macrae, *John Von Neumann: The Scientific Genius Who Pioneered the Modern Computer, Game Theory, Nuclear Deterrence, and Much More* (AMS Bookstore, 2000); Essinger, *Jacquard's Web*.
[11] Liu Suyi, "Fabric Weave Design Based on Cellular Automata Theory," May 15, 2009, 145–47, doi:10.1109/IUCE.2009.88.
[12] Franklin T. Moutos, Lisa E. Freed, and Farshid Guilak, "A Biomimetic Three-Dimensional Woven Composite Scaffold for Functional Tissue Engineering of Cartilage," *Nat Mater* 6, no. 2 (February 2007): 162–67, doi:10.1038/nmat1822.
[13] Gerard A. Ateshian, "Artificial Cartilage: Weaving in Three Dimensions," *Nat Mater* 6, no. 2 (February 2007): 89–90, doi:10.1038/nmat1830.
[14] K. Murasugi, "Knot Theory in Molecular Biology," *Knot Theory & Its Applications*, 2008, 267–83.
[15] Mahiar Hamedi, Robert Forchheimer, and Olle Inganas, "Towards Woven Logic from Organic Electronic Fibres," *Nat Mater* 6, no. 5 (May 2007): 357–62, doi:10.1038/nmat1884.
[16] Alexei Sossinsky, *Knots: Mathematics with a Twist* (Harvard University Press, 2004); P. Gerdes, "Fivefold Symmetry and (basket) Weaving in Various Cultures," *Fivefold Symmetry*, 1992, 245; Ada K Dietz, *Algebraic Expressions in Handwoven Textiles* (Louisville, Kentucky: The Little Loomhouse, 1949).
[17] Rizal Muslimin, "One-Piece Weaving: Reconfiguring Folding and Knotting Algorithm in Computational Design" (presented at the the 16th International Conference on Computer Aided Architectural Design Research in Asia (CAADRIA), Newcastle, Australia, 2011), 9–18.

weavers from the time they are newborns. The infants are swaddled and wrapped with cloth so that their upper arms are always close to their bodies. This conditioning helps build a posture that enables them to weave easily with the Zinacantec backstrap looms they use in their adult life. Additionally, Zinacantec children are introduced to toy looms as educational playthings at age three to seven. In their adult life, carrying a heavy load (of firewood) on their backs helps Zinacantec girls and women improve their balance for weaving. Nurturing such physiological capabilities from childhood provides a deep foundation for Zinacantec weavers to be more stable in backstrap loom weaving, while their childhood experience of sustaining visual attention (watching their mothers and sisters weave) prepares them to endure large weaving tasks, which usually take several weeks.[18]

While the Zinacantec developed their childhood education to support the practice of weaving, in another context it is the practice of weaving that helps support the children's education. According to Friedrich Froebel, the inventor of kindergarten, weaving cultivates the muscles in children's fingers, strengthening them and giving them greater flexibility, while training the children's vision to measure angles and distances. As they exercise their aesthetic tastes in selecting harmonious colors and patterns, their minds gradually gain the ability to work with objects with different relationships and properties. Froebel uses the playful logic of paper interlacing and mat weaving for his fifth and sixth occupation methods.[20] In addition to perception and motoric skills, Froebel's mat-weaving also stimulates children's intuition of numbers and arithmetical logic, as the child is obliged to count verbally while weaving.

1.2 Issues in Architectural Weaving

The brief background above shows the versatility of weaving in early architecture, computer science, and educultural domains. Given this versatility, the continuity of architectural weaving, from its inception to today's architecture, might have

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[18] Patricia Marks Greenfield, *Weaving Generations Together: Evolving Creativity in the Maya of Chiapas*, illustrated edition (School of American Research Press, 2004).
[20] Maria Kraus-Boelte and John Kraus, *The Kindergarten Guide: The Gifts.-V.8. the Occupations* (Nabu Press, 2010).

been seamless. Most architects today are consistently in pursuit of an inclusive design, where function, structure and aesthetics are logically interrelated within a building. This inclusive integration corresponds well with the values in weaving.

The inclusive model found in weaving, however, does not translate in most examples of recent architectural weaving. The relation between structure and the aesthetic features in some architectural weaving today is fragmented as the beauty of the building does not come from the structural expression. For instance, façade components may expresses weaving pattern or texture, but these components are not structurally woven. Moreover, some of the aesthetic expressions in this fragmented practice are trendless, bluntly mimicking the style from handicraft weaving. Existing weaving styles are magnified several times, a practical adaptation, but one that does not necessarily consider how these designs will perform when adapted to architectural scale.

This fragmented weaving and the trendless styles expose only the surface of the deeper problems. When we look beneath the surface issues of architectural weaving, we find issues that may be more conceptual than technical in nature. In particular, problems may arise from the conceptions under which weaving has been institutionalized, in both scholarly and industrial contexts.

In order to understand what has been left out of architectural weaving, we need to understand the difference between the features of handicraft weaving and the features of weaving that have been applied in architecture. To understand these issues more comprehensively, in the following segment I discuss the fragmented practice in architectural weaving, followed by the discussion on the fixation on weaving conceptualization.

Dormant Beauty in Architectural Weaving

In handicraft, weaving can be experienced through different modalities: visually, by admiring the pattern; physically, by feeling the texture and the stiffness; functionally, by utilizing the weave. Moreover, through the integration of visual, physical and functional qualities, the Vitruvian principles in weaving can be experienced intellectually.

However, in most architectural weaving, aesthetic expression is singled out from the rest of weaving qualities. This exclusion keeps weaving's Vitruvian principles dormant. In the following, I illustrate some examples on the aesthetic domination over structure in cases where building components are pseudo-woven. Subsequently, I contrast the trendless styles in architectural weaving with the progressive styles in handicraft weaving.

Pseudo-Woven

Despite the wide application of weaving's aesthetic in architectural projects, the structural features of weaving have not followed the aesthetic features at the same pace. Projects such as the Aragon Pavilion for World Expo 2008 in Zaragoza, the Spain Pavilion for World Expo 2010 in Shanghai, and the Center Pompidou Metz in Paris exhibit interwoven expressions aesthetically. Yet, on closer inspection, the components that express interwoven style in these projects are not *structurally* interwoven (Figure 2). In the Spanish pavilion, the weaving expression in the façade is assembled of curved woven-mat modules attached to the steel structure behind. In the Zaragoza pavilion, the wavy glass façade (constructed so as to create a weave-like impression), is sitting on a layer of zigzagged mullions. The Pompidou Metz probably bears the closest resemblance to the original interwoven pattern, as the triaxial timber pattern, in addition to its aesthetic function, does serve as a structural component. However, looked at in detail, the triaxial timber beams are basically stacked and layered one over another. In a traditional weaving structure, the component is not only stacked in an over-and-under configuration with the neighboring component but is also self-supporting with the others in a cyclical composition, in that some of the distributed load from one component to another will return back to itself.

Trendless Repetition

In addition to the lack of aesthetic-structural integrity in architectural weaving, the references to weaving styles in architecture are still limited compared to the diversity of weaving styles in handicrafts such as basketry and textiles. Not only does handicraft weaving show greater variety of style compared to architectural weaving, it is also more progressive. The structural logic and aesthetic expression in handicraft are well integrated and mutually resonant in the progression. For instance, the works of fiber artists such as Mary Jackson, Nathalie Miebach, and John Garrett in basketry, as well as Anni Albers and Stella Hicks in tapestry, exhibit new aesthetics of fiber design derived from ancient weaving techniques (plaiting, coiling, knitting, twilling, twinning, stitching, *ikat*, tatting, braiding, beading and many others). Permutations and combinations of various weaving techniques, supported with new materials and technology, have spawned numerous weaving styles in fiber art.

Indeed, the use of non-woven structural systems to support weaving expression is legitimate in architecture. Also, nothing is wrong with mimicking the exact style from the handicraft. My question from these practices is more about why weaving has yet to accommodate the Vitruvian model in architecture, given its corresponding principles. Moreover, with such progression in handicraft weaving, why is architectural weaving development relatively stagnant?

Understandably, a technical issue, in particular the characteristics of the material to be woven, is commonly regarded as one of the main reasons why the weaving diversity we see at the handicraft scale is difficult to adapt to the architectural scale. The vegetal materials used in handicraft weaving (e.g., reed, bamboo), which can be acquired easily from the surrounding environment, are flexible enough to be manipulated by hand (cut or bent), hence liberating the weaver to create various weaving configurations. In contrast, in architecture, the vegetal materials are considered inadequate to meet certain durability standards at building scale (e.g., structure, climate and safety). Additionally, handling industrial materials that are generally used in architecture is not as easy as manipulating the vegetal material used in in handicraft (Figure 3). Thus, architects might be encouraged to apply the material in architecture in the *same style* as the material is commonly applied in handicraft.

The examples above indicate that the problem in architectural weaving might be less about technical issues of *how to* apply weaving, and more about conceptual issues of perceiving *what* weaving *is*. Specifically, the problem is a general conception that registers weaving exclusively to the realm of handicraft and not to that of architecture. In the following, I explain how the conceptual issue of weaving-architecture incompatibility is rooted even deeper in handicraft categorization.

Design Fixation

The psychologists Jansson and Smith coined the term "design fixation" to argue that showing designers a picture of a potential design solution to a problem, prior to a design process, could result in fixation - that is, as a precedent, the picture would block access to the other ways of solving the problem.[21] [22] In supporting this theory, Jansson and Smith posit that a design process is operating with two types of mental representations of the design problem:

> *Conceptual space*: representation of abstract knowledge about principles, concepts and rules that can be used to solve the problem.
>
> *Object space*: representation of particular physical objects and elements that could form the physical realization of a solution to the problem.

Within these two mental spaces, design fixation occurs when a designer perceives a certain design precedent in the object space. The precedent solutions provided in this space will prevent the designer from moving to the conceptual space, where a new solution could produce an innovative design.

This theory might explain design fixations in architectural weaving, where some precedents from handicraft weaving seem to prevent architects from reinventing another way to weave on the architectural scale. Therefore, an architect may, in effect, copy and paste the precedent from handicraft into architectural scale as is. This study considers that fixation in architectural weaving may also be affected by the enumerative format in weaving studies and the well-established mechanization in weaving manufacturing.

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[21] David G. Jansson and Steven M. Smith, "Design Fixation," *Design Studies* 12, no. 1 (January 1991): 3–11, doi:10.1016/0142-694X(91)90003-F.
[22] A. Terry Purcell and John S. Gero, "Design and Other Types of Fixation," *Design Studies*, Special Issue: Design Cognition and Computation, 17, no. 4 (October 1996): 363–83, doi:10.1016/S0142-694X(96)00023-3.

Enumerative Catalogue: Fragmented Styles

A long list of weaving types has been documented and categorized by many scholars. For instance, in categorizing lightweight structures, Frei Otto defines various types of netting.[23] In exemplifying basic types of textiles, Annie Albers defines several types of weaves (e.g., coiling, netting).[24] In proposing weaving as the first element in architecture, Gottfried Semper distinguishes several basic types of weaving (e.g., knitting, plaiting, and knotting).[25] In cataloguing basketry across culture, Bryan Sentance geo-tags different styles of basket weave based on location (e.g., African weaving, Navajo weaving, Japanese weaving).[26] This enumerative weaving documentation is important to exhibit the diversity of weaving as well as to promote the craft of related culture.

Nevertheless, beyond these meticulous catalogues, certain information that is needed for design purposes is not addressed by the enumerative format. The broad spectrum of stylistic weaving in the catalogues provides many precedents for an architect to apply architectural weaving in the *object space* mode (according to design fixation theory). However, the knowledge needed to learn the basic principles and rules of weaving--to reinvent architectural weaving in the *conceptual space* mode--is not available in the enumerative format. Some books give step-by-step instruction for how to build a specific weaving style, yet this instruction does not describe the weaver's design method – how he or she invented the style.

In addition, the absence of other types of crafts in the catalogues that use weaving principles but with different names, materials, or scales, could also cause design fixation. These exclusions could cause any potential ideas and principles from the so-called 'not weaving' to be perceived as incompatible with architectural weaving, and thus, would not be considered in the architect's *conceptual space* during the design process.

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[23] Berthold Burkhardt, Jugen Hennicke Frei Otto, *IL 10 - Grid Shells* (Institute for Lightweight Structures, University Stuttgart, n.d.).
[24] Anni Albers, *On Weaving* (Wesleyan University Press, 1965).
[25] Semper, *The Four Elements of Architecture and Other Writings.*
[26] Bryan Sentance, *Basketry: A World Guide to Traditional Techniques* (Thames & Hudson, 2007).

Mechanical Fixation: Binary Weaving

To understand how far weaving design has evolved, it is necessary to distinguish design innovation from manufacturing revolution.

Weaving automation, as a means to delegate the role of the weaver's body to an external apparatus, may have begun in prehistoric times.[27] Prehistoric weavers at that time invented ways to fix several threads in one orientation all at once (warp) with a cane or hanging branch so they could weave another thread (weft) in perpendicular orientation to the warp (this process later became known as looming).

In their time, the prehistoric weavers' precedents probably came from random weaving in nature (e.g., birds' nests). In revolutionizing weaving design, they were able to think beyond these precedents by simplifying the random weaving in nature into a two-axis *plain weave* that remains pervasive today (i.e., a two-strands rectilinear weave composition).

This prehistoric invention liberated the weaver's hand from handling several vertical warps at once and let the weaver focus solely on sliding the horizontal weft through the warps. Subsequently, for the next few thousands of years, through a series of looming mechanization advances (e.g., frame-support, shuttle, and yarns), the process of sliding the weft and lifting the warp remained in the weaver's hand until the beginning of the 19th century. As the role of the hand was delegated to the punched card in the Jacquard loom, weaving became hands-free. Thus, in terms of manufacturing, weaving mechanization has been advanced through many generations since prehistoric weaving.

However, in terms of design, most of today's industrial weaving is essentially weaving the same design that was invented by the prehistoric weaver

[27] Mattie Phipps Todd, *Hand-Loom Weaving: A Manual for School and Home* (Rand, McNally & company, 1902); Alfred Barlow, *The History and Principles of Weaving, by Hand and by Power* (London: Low, Marston, Searle, & Rivington, 1878).
The conception of automation used in this framework is based on Bruno Latour, """Where Are the Missing Masses? The Sociology of a Few Mundane Artifacts,""" in *Shaping Technology / Building Society: Studies in Sociotechnical Change*, by Wiebe E. Bijker and John Law (Cambridge, Mass.: The MIT Press, 1994); Bruno Latour, "Gaston, A Little Known Successor of Daedalus," trans. Charis Cussins, n.d.

thousands of years ago: plain weave and its variations (e.g., basket weave, satin, twill, etc.). A contributing factor in the design fixation on this mechanization might be the hands' lessening involvement in weaving over time. Consider a weaver holding a thread in each hand. There are many ways for the weaver to weave the threads in 3D space to create points, linear, planar, or volumetric objects (e.g., a knot, a braid, a mat or a basket). However, the first weaving automation into looming effectively reduced the number of possible ways to weave in 3D space into 2D space (fabrics) with 1D linear motion (i.e., by sliding the weft only horizontally). The weaving advancement in the Jacquard loom completely lifted the hand off the thread and only left patterns of 0D points on a surface, ready to be flipped between '0' and '1' to portray a pixilated 2D image -- hands off; codes on.

Thus, if the enumerative catalogue effects design fixation visually, then weaving automation effects design fixation mechanically.

1.3 Research Statement

I have explained some issues in today's weaving application in architectural design, such as pseudo-weaving and trendless repetition. I have also discussed some potential issues in reinventing architectural weaving, such as weaving mechanization and weaving enumeration. On that basis, strategies to reinvent architectural weaving are outlined as follows: [1] To prevent the mechanical fixation, we need to shift attention back to the condition before the weaving process was mechanized and digitized (i.e., hand-weaving), and focus more on interpreting weavers' methods during the weaving process. [2] To prevent design fixation, we need to pair the enumerative representation of weaving *products* with a generative representation of weaving *processes* that could demonstrate the basic principles and rules of weaving design. Using these strategies could help architects to analyze existing weaving designs and synthesize new weaving designs for the architectural scale.

To pursue these strategies, the main objectives of this research are the following:

Interpretation. In order to analyze weaver methods before weaving mechanization, the analysis would need to take place in a traditional setting where non-mechanized weaving practice and natural weaving materials are available. Traditional weavers often make use of tacit knowledge. To anticipate and capture tacit knowledge in the traditional setting, this study develops *EthnoComputation,* a research method to interpret a weaver's actions and perceptions into explicit representations.

Reinvention. To create a generative representation that resonates with the basic principles of weaving, the representation would need to be obtained from a rule-based design that encapsulates characteristics of weaving designs. This study formulates two *Weaving Grammars*: Basic weaving grammar and Abstract weaving grammar,a set of design rules that is capable of characterizing existing weaving design as well as generating new weaving designs.

1.4 Methodologies

To support the interpretation and reinvention strategies, four research methodologies are used -- Shape Grammar, FEM, *In Situ* Research and Perceptual System Theories. These four methodologies function both as an analytical platform to interpret the logic of weaving based on weaver-weave interaction, and as a synthesis platform to demonstrate the reinvention of weaving into architectural scale.

Shape Grammar

Shape grammar, originated by George Stiny and James Gips in 1972, is a computational design method used to analyze and synthesize designs by embedding and calculating shapes with a set of shape rules.[28] A *shape rule* is visually represented by a left-hand shape and a right-hand shape (the new shape). A shape in the rule can be defined by a certain parameter or description (e.g.,

[28] George Stiny and James Gips, "Shape Grammars and the Generative Specification of Painting and Sculpture," *Information Processing* 71, no. 1460–65 (1972): 125.

variables, conditions and data set). A *shape computation* represents the iteration of shape rules in a step-by-step notation to show how the rules generate designs.

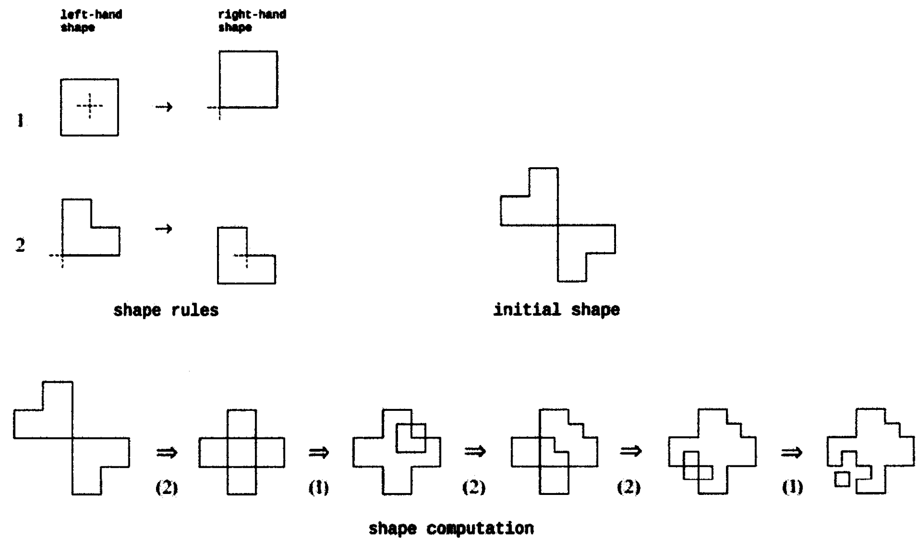

Figure 1. Shape Grammar Computation [29]

Most shape grammar studies for design analysis are represented by defining the shape rule first, and then showing how the rules generate designs in a shape computation. In addition to this procedure, the present study also uses each shape rule and shape computation as a stand-alone function to represent information from traditional settings and knowledge from different disciplines.

For representing knowledge from traditional settings, such as crafting activity, shape computations can independently serve as a recording instrument to visually and explicitly document the iterative process of craftspeople's activities. With this explicit representation, the iterative process of the craftsperson becomes more amenable for computational analysis.

In representing knowledge from different disciplines, such as descriptions from applied sciences, shape rules can accommodate certain scientific descriptions in the shape rules. In the form of shape rules, the descriptions from the other disciplines can be more easily be incorporated into a design synthesis.

[29] From: Terry Knight, "Computing with Emergence," *Environment and Planning B: Planning and Design* 30, no. 1 (2003): 125–55, doi:10.1068/b12914.

(More details regarding shape grammar's principles will be presented in chapter 2.)

Finite Element Method

Finite Element Method (FEM) is a method for analyzing the structural response of a physical object that has been idealized into a virtual model (i.e., an assemblage of vertices, edges, and faces called finite elements, which define the shape of the object). Given the volume of the object, boundary conditions, degree of material elasticity (Young's Modulus), and the applied external load on the model, FEM solves the structural response of the idealized object by satisfying the Equilibrium Solution (based on Hooke's Law) of each element inside the body and on the surface.[31] [32]

This research uses FEM at two levels: the application level and the conceptual level. At the application level, this study uses FEM simulation software and compression testing to analyze the structural behavior of rule-based weaving design under different design rule parameters. At the conceptual level, this study revisits the FEM idealization process in converting a physical object to a virtual model. This conversion is represented with shape grammar notation, in order to integrate computational design and computational mechanical features early in the process of designing architectural weaving. This integration is used to analyze and synthesize potential weaving derivations in the other type of crafts (e.g. tensegrity, beading, folding, etc.). (More details on the Finite Element Method idealization process will be presented in chapter 3.)

***In Situ* Research**

This study uses three types of *in situ* research: (1) field observation, (2) a weaving grammar workshop and (3) a building installation workshop, to observe traditional weaving knowledge on the site and to inspect the adaptation of the rule-based design on the site.

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[31] Klaus-Jürgen Bathe, *Finite Element Procedures* (Englewood Cliffs, N.J: Prentice Hall, 1996).

[32] Miguel Luiz Bucalem and Klaus-Jurgen Bathe, *The Mechanics of Solids and Structures - Hierarchical Modeling and the Finite Element Solution*, 2011 edition (Berlin; New York: Springer, 2011).

Field Observation. The observation included a *general observation* of the surrounding environment on the site to note activities and elements related to weaving, and *specific observation* of the weaver's interaction with the weave during the making process.

Weaving Grammar Workshop. This workshop included teaching rule-based weaving design to groups of participants to evaluate their degree of comprehension in understanding a rule-based design approach.

Building Installation Workshop. In this installation, a group of local carpenters built a mock-up of an architectural weaving installation in the field to evaluate the degree of applicability of a rule-based design during the construction process in a traditional context.

The primary site for my *in situ* research was Kete Kesu, a traditional village in Toraja, Indonesia, chosen for its rich diversity of crafts. A secondary site of my field study was Cambridge, Massachusetts, where I conducted a 'Weaving Grammar' workshop for a group of 5th to 9th graders to assess weaving grammar's universality across age groups.

Perception System Theory

This study also incorporates a theory of perception to analyze the traditional weaver sensorial experiences during the weaving process: James Gibson's 'Perceptual Systems'.[33]

1.5 Scope of this Work

The Method, not the Subject

The scope of research in the field study is microscopic, concentrating on a specific interaction between a traditional weaver with a specific weaving design, parsed in a very definite moment, and geographically confined in a remote location. Thus, although the weaving procedures in this definite moment are omnipresent

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[33] James Jerome Gibson, *The Senses Considered as Perceptual Systems* (Boston: Houghton Mifflin, 1966); James Jerome Gibson, *The Ecological Approach to Visual Perception* (Routledge, 1986); E. Bruce Goldstein, "The Ecology of J. J. Gibson's Perception," *Leonardo* 14, no. 3 (Summer 1981): 191–95.

beyond geographical boundaries and across cultures and periods, the ubiquity of weaving should not position this study as a generalization of weaving.

Through the field research, this thesis should be seen as a proposal for a design method on how to learn design from the weaver – here, in particular, from the tacit environment of traditional weaving. The research should not be evaluated with a statistical mindset so as to legitimate a certain weaving method based on quantitative findings. The value of this study should be appraised according to the capacity of the research method to extract information from the designer's activity and transform it into an explicit knowledge for design purposes.

The Process, not the Product

The scope of design generation is limited to generating a very specific architectural component that demonstrates weaving principles, instead of a whole building configuration. Yet the process of developing this architectural component encompasses several phases: interpreting design knowledge from the traditional weaving, formulating the design knowledge into a Weaving Grammar, teaching the Weaving Grammar back to local people, and testing the buildability of the architectural component (generated from the Weaving Grammar) using the local skills and local materials at the site.

Therefore, the conception of architecture in this thesis is not confined solely to the architectural component, but rather extended through the cycle of the component's design derivation *from* a traditional site, and its application back *to* the traditional site. Thus, the evaluation should be made on the comprehensibility of the Weaving Grammar in a traditional context, and the Grammar's capacity to analyze and synthesize weaving designs.

1.6 Thesis Outline

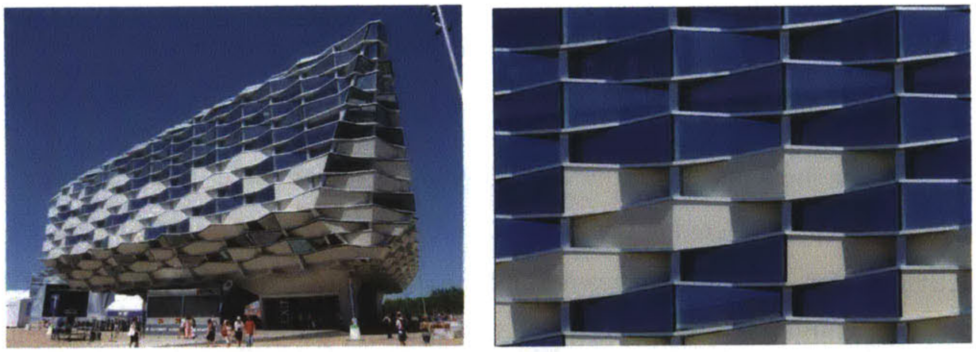
This thesis is divided into four parts, beginning with this introduction (part one).

The second part, "EthnoComputation," outlines my computational approach (EthnoComputation) in assessing and demonstrating the analytical use of shape grammar to observe traditional weaving activities. The procedures of the EthnoComputation study are computationally detailed and findings from the observation are presented visually.

The third part, "Computational Weaving," formulates two weaving grammars, Basic Weaving Grammar and Abstract Weaving Grammar, based on activities of the traditional weaver and theories from Shape Grammar and Finite Element Method. Case studies (including weaving grammar workshops, building workshops), as well as demonstration of designs generation from the Weaving Grammars are outlined to demonstrate the process of reinventing weaving for an architectural scale.

The fourth part, "Conclusion," summarizes and discusses the role of computational design in interpreting and reinventing weaving in architectural design and envisioning the future work of EthnoComputation and architectural weaving.

a.



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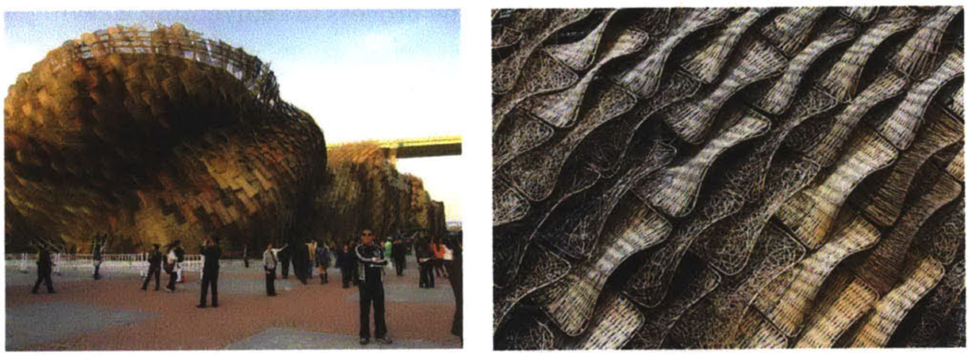

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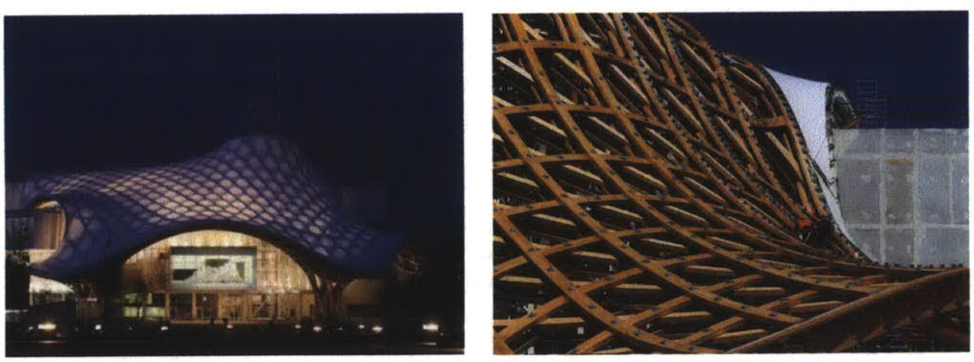

Figure 2. Pseudo-Woven

Architectural weaving from the left: [a] Aragon Pavilion for World Expo 2008 in Zaragoza by Olano and Mendo,[34] [b] Spain Pavilion for World Expo 2010 in Shanghai by Benedetta Tagliabue,[35] [c] Center Pompidou Metz in Paris by Shigeru Ban.[36] Close up images on the bottom of each building show façade components expressing the aesthetic of weaving, yet structurally, the components are not interwoven.

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[34] Images available from: http://en.wikipedia.org/wiki/Zaragoza and http://www.panoramio.com/photo/26703814

[35] Images available from: http://commons.wikimedia.org/wiki/File:Spain_Pavilion_of_Expo_2010_2.jpg and https://www.flickr.com/photos/13286981@N04/5360958173/

[36] From: http://www.archdaily.com/490141/centre-pompidou-metz-shigeru-ban-architects/ and http://www.checkonsite.com/centre-pompidou-metz/comment-page-1/?pid=870

a b

Figure 3. Woven Bentwood and Sculptural Weaving
[a] Frank Gehry's Knoll Chair (Power Play) is woven with Bent wood technique using hard white maple veneer strips[37] and [b] Frank Gehry's Fish Sculpture at the top of Vila Olympica in Barcelona is woven with Bronze Strips and supported by steel frame structure from behind.[38] The Fish is woven using a similar type of weave as the Knoll chair (i.e., plain weave).

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[37] From http://areaneo.com/blog/2013/05/10/frank-gehry-lounge-chair-power-play-for-knoll-international-1992/ and http://hivemodern.com/pages/product537/knoll-frank-gehry-power-play-lounge-chair
[38] From: http://www.europaenfotos.com/barcelona/eng_pho_bcn_175.html and http://www.shutterstock.com/pic-30686695/stock-photo-barcelona-april-frank-gehry-s-peix-d-or-whale-sculpture-on-the-beach-of-barcelona-april.html

2 ETHNOCOMPUTATION

2.1 Outline

This chapter describes my field study, in which I used computational means to interpret the craft of weaving in a traditional village in Toraja-Indonesia. In the field study, the craft of weaving is analyzed beginning from the acquisition of materials from nature (bamboo) to the weaving process itself.

Challenges of interpreting crafting activity in this context lie in representing, explicitly, the tacit knowledge in traditional practice.[39] The indigenous craftspeople in this field study craft with skills passed down from generation to generation. They work based on sensory input from engaging with their tools and materials (e.g., sight, touch, sound, smell and taste). They learn tacitly, by observing other craftspeople's activity and other crafts objects, rather than by attending formal institutions with explicit instructions and design theories. To represent this tacit knowledge, I observe a craftsperson's activity and analyze his observable interactions with the craft object, i.e., eyesight direction, hand contact and body movement. From this interaction, I interpret the craftsperson's sensorial experience explicitly through computational representation. To represent how he learned from other works, I observe the variety of crafts objects that are available on the site, and interpret the crafting process into computational rules.

The chapter is divided into five sections. The first section situates my computational approaches through reflections on other disciplines' work in traditional communities; in particular, I reflect on the ways in which scholars analyze and represent traditional craft in their case studies. Based on this reflection, I propose my *in-situ* research methods, *EthnoComputation,* which are

[39] Michael Polanyi, *Knowing and Being: Essays by Michael Polanyi,* First Edition edition (Chicago: University Of Chicago Press, 1969).

built upon Shape Grammar principles. A discussion of how Shape Grammar principles describe traditional crafting processes on the site is provided.

The second, third and fourth sections describe my EthnoComputation method in interpreting weaving activities, from three perspectives: [a] from a general observation of the site, [b] from an observation of weaving's material derivation from nature into crafts components and [b] from focused observations on the weaver-weave interaction.

The second section demonstrates how EthnoComputation works on visual observation by showing the application and benefits of *seeing-in-there* in conjunction with *being there.*[40] I illustrate my procedures for representing a traditional village as my site, and for delineating the scope of my research through visual computation. From the visual computation, I generate several reconfigured sites, each of which can be experienced and studied from different perspectives. Two of the reconfigured sites highlight relationships between craftsperson, craft objects and the nature. The relationships highlighted in these two frameworks serve as the research framework for the third and fourth sections.

The third section interprets how nature is translated into material for the craft of weaving. Drawing upon Aristotle's matter and form conception (*hylomorphism*),[41] [42] through an interpretative computation, I associate the abundance of bamboo as the main weaving material and the diversity of bamboo crafts in the villages. I develop rules and schema to exemplify how craft material is made from two directions: by reverse-engineering the material manufacturing process back to nature and by generatively deriving the natural material into a diverse type of craft component. This interpretation highlights a pivotal assumption about how the weaver perceives a shape, an assumption I use as I observe the weaving process, as detailed in the fourth section.

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[40] Clifford Geertz, *Works and Lives: The Anthropologist as Author*, 1 edition (Stanford, Calif.: Stanford University Press, 1989).

[41] Christopher Shields, "Aristotle," in *The Stanford Encyclopedia of Philosophy*, ed. Edward N. Zalta, Spring 2014, 2014, http://plato.stanford.edu/archives/spr2014/entries/aristotle/.

[42] Frank A. Lewis and Robert Bolton, *Form, Matter, and Mixture in Aristotle* (Oxford, UK; Malden, MA: Wiley-Blackwell, 1997).

The fourth section describes the interaction between the weavers and weaves during the weaving process. Based on my observations on the site, I present the weaver's sensorial interaction with the weave through an iterative computation. The sensorial interaction is represented within two timeframes: slow motion and fast motion. In the slow-motion analysis, the analysis focuses on the weaver's visual and haptic interactions with the weave, to interpret shapes that the weaver embedded perceptually in the weaving process. In the fast-motion analysis, I analyze the weaver's body orientation toward the weave, as he moves from one position to another, to understand how the weaver views the shapes as he adds a thread on the weave in different positions.

The discussion in the last section of this chapter reflects on how traditional weaving activities, as a tacit knowledge, can be interpreted by an observer using the EthnoComputation approach.

2.2 Introduction

In situ research of traditional crafts has focused on different subjects, including ornamentation study, such as Franz Boas's documentation of the art of North America's North Pacific Coast,[43] socio-symbolic study, as seen in Roxana Waterson's documentation of the cosmological aspects of Southeast Asia's traditional houses,[44] and socio-educational study, exemplified by Patricia Greenfield's study of the social dimension of back-strap looming activities in Zinacantán, Mexico.[45]

Examined by researchers of various backgrounds and built upon a multidimensional cultural foundation, traditional-craft studies inevitably lead to several disciplinary convergences; each discipline focuses on a specific aspect of the craft. Two disciplines that intersect with computation and visual material are

[43] Franz Boas, *Primitive Art*, 1st Dover Edition (Dover Publications, 1955).
[44] Roxana Waterson, *The Living House: An Anthropology of Architecture in South-East Asia* (Tuttle Publishing, 2010).
[45] Greenfield, *Weaving Generations Together.*

ethnocomputing, which study the application of computing in cultural settings,[47] and *visual ethnography*, which study the use of visual media and material, as well as the incorporation of a visual lens into ethnography.[48]

The explicit representation and visual awareness proposed in these fields coincide with my objective in studying weaving in the traditional context. Nevertheless, considering that visual ethnography originated from social sciences and that ethnocomputing was derived from computer science, it is necessary to understand how the views of craft in these disciplines intersect with the view of craft in this thesis. In this thesis, I view craft as a design activity. How are the perspectives from which scholars in visual ethnography and ethnocomputing describe the crafting process, and present it to their audiences, useful to design? How might a design study diverge from these perspectives?

The Visual in Visual Ethnography

Visual anthropology is generally known as an anthropological practice using a visual medium, as well as a study of visual phenomena in culture and society.[49] The notion of what visual means in a certain culture and how to capture visual culture through a visual lens has held the spotlight in academic debates in visual anthropology. As a method in visual anthropology, visual ethnography has been re-defined, promoted and criticized among anthropologists. Anthropologist and ethnographic filmmaker David MacDougall is a strong critic and also a leading advocate of visual anthropology. MacDougall builds upon his concern for the textual narration of visual material, exclusive of ethnographic film studies, and the myopic view of the use of visual technology for anthropological practice rather than the visual form of anthropology to re-conceptualize visual anthropology in his responses to the earlier *Principles of Visual Anthropology* proposed by Paul Hocking.[50] In *The Corporeal Image*, MacDougall posits three principles:

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[47] Tedre Matti, "Ethnocomputing: A Multicultural View on Computer Science" (M.Sc Thesis, University of Joensuu, 2002).
[48] Karen O'Reilly, *Key Concepts in Ethnography* (SAGE Publications Ltd, 2014).
[49] *Encyclopædia Britannica Online*, s. v. "visual anthropology," http://www.britannica.com/EBchecked/topic/1072842/visual-anthropology.
[50] Paul Hockings, *Principles of Visual Anthropology*, 3 edition (Berlin: De Gruyter, 2003).

> *(1)To utilize the distinctive expressive structure of the visual media rather than those derived from expository prose; (2) To develop forms of anthropological knowledge that do not depend upon the principles of the scientific method for their validity; (3) To explore areas of social experience for which visual media have demonstrated expressive affinity —in particular (a) topographic, (b) the temporal, (c) the corporeal, and (d) the personal.*[51]

MacDougall's principles imply an invitation for visual ethnographers to build more confidence in the validity of anthropological knowledge and ethnographic method in studying the visual media and visual culture. His principles of visual anthropology were later echoed by social anthropologist Sarah Pink, who defined ethnography as a "methodology; as an approach to experiencing, interpreting and representing culture and society that informs and is informed by sets of different disciplinary agendas and theoretical principles".[52]

Pink further underlines the role of the ethnographer's *personal experience in representing knowledge* that does not claim to produce an objective or truthful account of reality, but rather an '*individual experience of reality*'.[53] In other words, the same reality will be experienced differently by different individuals with different reasoning and perceptions. These differences would lead to different findings (Figure 6). In practice, the content of visual ethnographic studies ranges widely. In terms of visual material, the studies range in coverage from the visual material *owned by* a subject, to the subject activity *as the* visual material. In terms of visual media, the studies range in coverage from the technology used to capture the visual material (Figure 4), to the media used to publish the visual material (Figure 5).

[51] David MacDougall, *The Corporeal Image: Film, Ethnography, and the Senses* (Princeton, N.J: Princeton University Press, 2005).
[52] Sarah Pink, *Doing Visual Ethnography*, Second Edition edition (SAGE Publications Ltd, 2012).
[53] Ibid.

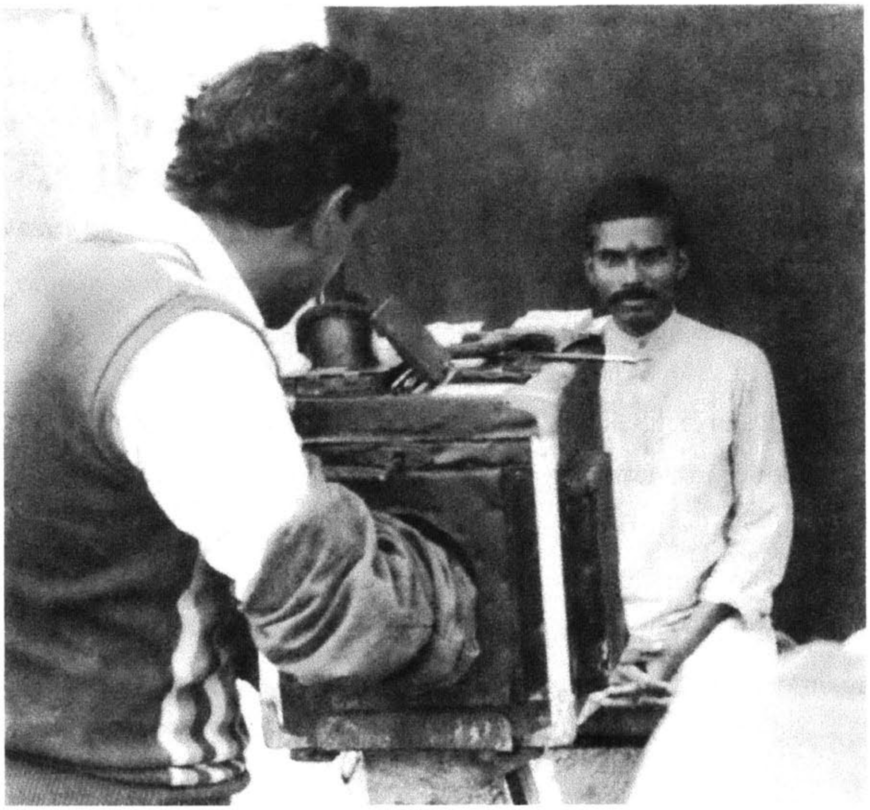
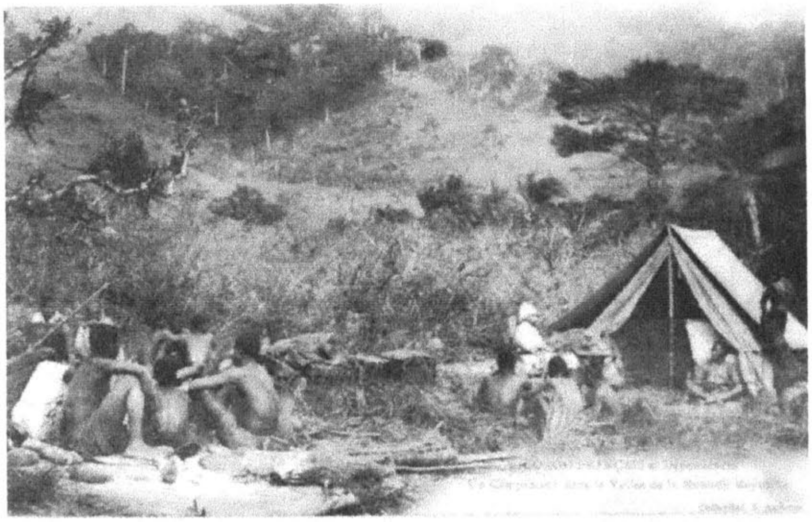
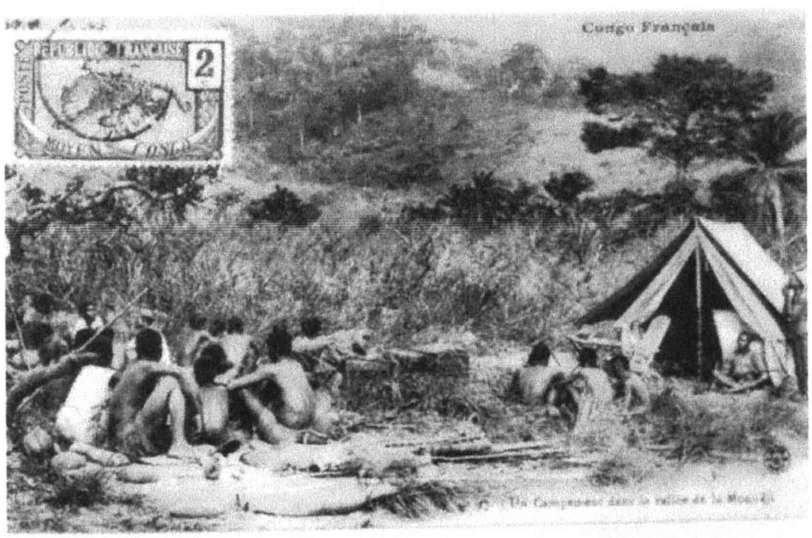


Figure 4. Street photographer in Dehra Dun, India, 1989 [54]
People and devices in this picture are a few of many subjects from MacDougall's visual anthropology study, which covers multi-dimensional aspect of photographic practice in India, ranging from the social life of the photographer to the context and history of the practice to the mechanism of the camera.

[54] From: MacDougall, *The Corporeal Image*. p.157



7.1a. "Un Campement dans la Vallée de la Moundji Mayumbe," postcard by J. Audema, French Congo, ca. 1905.



7.1b. "17. Un Campement dans la vallée de la Moundji," postcard by J. Audema, French Congo, ca. 1905.

Figure 5. The Disappearing European man, 1905 [56]

Two postcards by French photographer, Jean Audema, at the French Colonial in Mayumbe, Congo, serve as MacDougall visual material for his study on the colonial photographer. Visual anthropological study from this image can go far beyond the intriguing subject in the picture (i.e. the disappearance of the bearded European in the one picture and ways of posing the natives); for instance, the postcard itself as a visual medium along with its embedded properties: caption, written text, style, public tastes, etc.

[56] From: MacDougall, *The Corporeal Image.* p.177

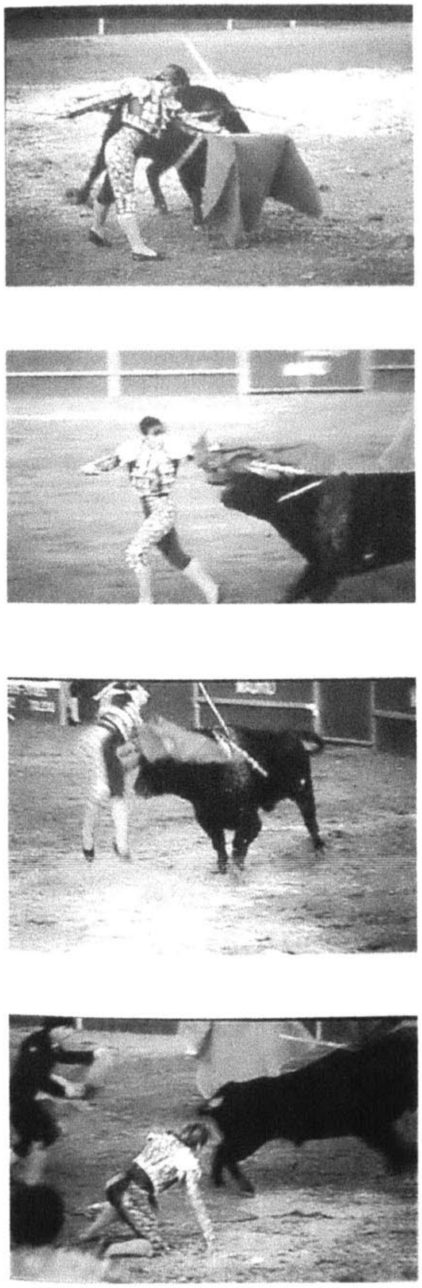


Figure 6. Women in Bullfighting [58]
Pink illustrates three possible interpretations of the sequence of these images from three groups of people: [1] fans who support women as matador, [2] fans who are skeptical about the idea of a 'women matador' and [3] people who are against bullfighting. The top image may entertain the first group, while the other images may justify skepticism in the other group, i.e., that women shouldn't perform in bullfighting (group 2) or that the bullfighting itself should be banned (group 3).

[58] From: Sarah Pink, *Doing Visual Ethnography*, Third Edition edition (SAGE Publications Ltd, 2013).p.77

The Computation in Ethnocomputing

In a more formal discipline, a group of computer scientists approach the traditional site through digital representation. Drawing from his concern on the dominant 'western' culture in computer science education in developing countries, Tedre Matti, a computer scientist, offers the term *ethnocomputing*, as "a field of research that studies the phenomena and applications of computing in different cultural settings". Here the term "computing" refers to the use of computer applications in an educational context. In his thesis, Matti proposes ethnocomputing as a "tool for developing a multicultural approach in Computer Science education, recognizing the influence of societal and cultural backgrounds on learning Computer Science."[60]

Matti's illustration of indigenous crafts as exemplifying ethnocomputing practice, such as Marcia Ascher's study of the Inca Quipu[61] and Ron Eglash's study of the African fractal[62], is mostly metaphorical. The computing aspect of the craft is proposed by mapping properties of computer language onto features found in the artifact (e.g. color coding and number of knots in Quipu). Matti looks at Quipu as "a structure that represents organized information, and can be considered as a data structure".[63] Matti has continued to work in Information and Communication Technology (ICT). His projects are conducted primarily in rural settings in Ethiopia, Colombia, Tanzania, South Africa, and Sri Lanka, where he uses computers to analyze how students interact with teaching materials. The original concept generated in Matti's thesis, *computing = computer*, continues as the model in ethnocomputing research (Figure 7). Recent ethnocomputing studies seem to focus mainly on understanding how ICT affects and interacts with society and culture.[64]

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[60] Matti, "Ethnocomputing: A Multicultural View on Computer Science."
[61] Marcia Ascher, *Mathematics of the Incas: Code of the Quipu* (Dover Publications, 1997).
[62] Ron Eglash, *African Fractals: Modern Computing and Indigenous Design*, 3rd edition (New Brunswick, N.J: Rutgers University Press, 1999).
[64] Matti Tedre et al., "Ethnocomputing: ICT in Cultural and Social Context," *Commun. ACM* 49, no. 1 (January 2006): 126–30, doi:10.1145/1107458.1107466.
[64] Matti Tedre et al., "Ethnocomputing: ICT in Cultural and Social Context," *Commun. ACM* 49, no. 1 (January 2006): 126–30, doi:10.1145/1107458.1107466.

Ron Eglash, who supports Matti's definition of ethnocomputing, is probably closer to the design discipline. Eglash's ethnocomputing studies aim to help students learn math using indigenous design and digital simulations.[66] This scope is apparent in his interactive digital representation of traditional design, such as the African Fractal software, to produce a computer-generated design resembling traditional designs. On his website, "Culturally Situated Design Tools: Teaching Math and Computing through Culture," Eglash provides Internet access to various simulators of the traditional design. Under the title, there is an encouraging description about the software:

> *Many cultural designs are based on math and computing principles. This software will help students learn these principles as they simulate the original artifacts, and develop their own creations.*[67]

However, the simulator does not show the design process or how the craftsperson interacts with the design. The software lets the user generate the design by typing an input for the design parameter -- for example, the shape position (point coordinate), symmetrical properties (rotation angle), and recursive function (number of steps). Thus, what the user will learn from the software, as promised, is the math and computer principles. To be precise: users learn the Principle of Fractal, which may or may not relate to the original design principles. After I tried the software, the website description looked different to me:

> *Many ~~cultural~~ designs ~~are based on~~* ***can be explained*** *with ~~math and computing~~* ***fractal principles.*** *This software will help students learn these principles as they simulate the ~~original~~* ***fractal shape that is similar to existing designs,*** *and develop their own ~~creations~~* ***fractal design.***[68]

Eglash himself did not claim that his fractal description is the main concept underlying the African built environment. In *African Fractals*, he

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[66] Ron Eglash et al., "Culturally Situated Design Tools: Ethnocomputing from Field Site to Classroom," *American Anthropologist* 108, no. 2 (June 1, 2006): 347–62, doi:10.1525/aa.2006.108.2.347.
[67] Ron Eglash, "Culturally-Situated Design Tools," *Culturally Situated Design Tools: Teaching Math and Computing through Culture*, accessed May 16, 2014, http://csdt.rpi.edu/.
[68] The software is still fun to use (if not addictive). However, after several design iterations, my initial appreciation on the unique traditional design has shifted into the universality of the symmetry. From the software, I appreciate the fractal more than the traditional design. What left from the cultural notion is simply the ethnic-label indicating the place where the artifact found.

acknowledges, "African fractal geometry is not a singular body of knowledge, but rather a pattern of resemblance that can be seen when we describe a wide variety of African mathematical ideas and practices, and it is not the only pattern possible".[69] For Eglash, the Fractal representation of African artifacts is a *thin description*, a study of surface particularities of an artifact. [70] The question of whether the artifact may or may not symbolize deeper meaning than the fractal appearance is out of the scope of his thin description.

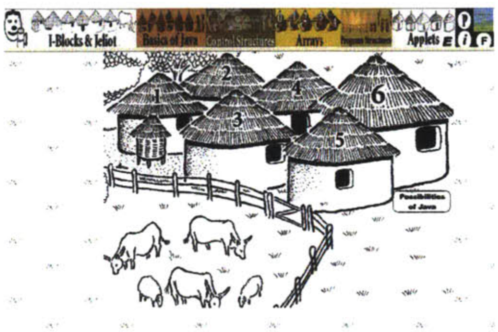

Figure 7. Introduction to Java Programming Language in Tanzania [71]
Local traditional houses used as a graphic metaphor for the online-programming course. The metaphor used to make the course material become familiar is easily grasped by the learners.

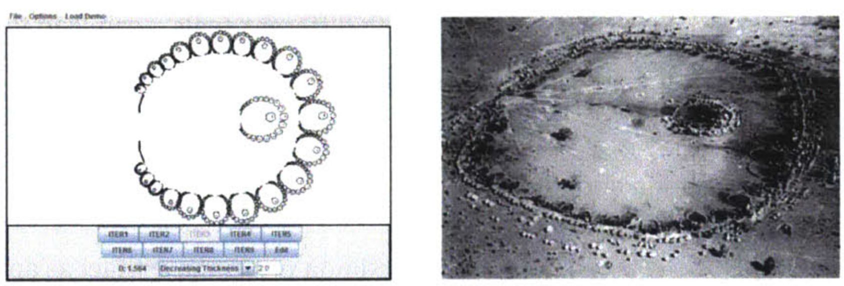

Figure 8. African Fractal simulation [72]
Using a set of fractal algorithms, the software (left) generates shapes that are similar to the top view of the Ba-ila village, Zambia (right). The iteration button (e.g., ITER1, ITER2) shows different steps of fractal iteration The same software simulates other traditional artifacts in Africa that can be explained using Fractal principles.[73]

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[69] Eglash, *African Fractals.* P.182
[70] Ibid. p.181, in response to Clifford Geertz "Thick Description", that criticize structuralism approach in reducing the cultural symbols into a mechanistic syntax.
[71] From: Mikko Vesisenaho Erkki Sutinen, "Ethnocomputing in Tanzania: Design and Analysis of a Contextualized ICT Course.," *Research and Practice in Technology Enhanced Learning* 1 (2006): 239–67, doi:10.1142/S1793206806000238.
[72] From: Eglash, "Culturally-Situated Design Tools." http://csdt.rpi.edu/african/African_Fractals/culture4.html
[73] Ibid. See http://csdt.rpi.edu/ for more example of Eglash's Fractal program.

The EthnoComputation Approach

The above reflection provides a new path for me to situate my approach to observing traditional weaving on a field study site. My aim in this field study corresponds to a visual ethnography project in terms of drawing a distinctive picture of a mix of knowledge, through personal experience on the site. My aim also parallels the ethnocomputing practice of representing the local knowledge explicitly, based on observations of the artifact, without verifying the cultural symbol or meanings underlying the artifact. However, this field study does not aim to promote digital technology or apply a particular logic to a traditional object, as demonstrated in ethnocomputing. Nor does it advocate for a particular culture, nor debate the use of the visual media as visual anthropology does. This study aims to understand how craft is perceived during the making process, by interpreting human-craft interaction explicitly in the traditional context.

In studies of traditional craft, the crafts objects themselves are often viewed as artifacts; the culture in which they are produced is viewed as the context for their creation. In this study, I view culture as the way humans represent how they understand their environment. Different understandings of the environment -- seeing it in different ways, with different goals -- can lead to different representations (i.e., the creation of different kinds of objects). From this perspective, the craft object itself is not the artifact; the artifact is in the interaction between a person and the object.

In *The Sciences of the Artificial*, Herbert Simon posits the artifact as an interface between an inner environment and outer environment -- that is, "if the inner environment is appropriate to the outer environment, or vice versa, the artifact will serve its intended purpose".[74] For example, as an artifact, a bird's wing serves as an interface. Observers of the bird's wing interpret how the inner and outer environment interacts in the bird's flying mechanism. In aerospace engineering, the interpretation has been focused on the shape of the bird's wing, and has led to different types of airfoil for artificial flying. Different observers may have different interpretations, or focus on a different aspect of the inner-outer

[74] Herbert A. Simon, *The Sciences of the Artificial - 3rd Edition*, 3rd ed. (The MIT Press, 1996).

environment of a bird's wing; such different interpretations could lead to different innovations. A different focus on the bird's wing -- a focus on the flapping mechanism, rather than on the shape -- helped the Festo Company develop a bionic bird that can fly by flapping and twisting its wing (instead of using turbine) in their *SmartBird* project.[75]

Drawing from Simon's framework, I assign the term "artifact" in this study to the interface between objects and the craftsperson, i.e. the craftsperson's tacit knowledge and perceptual system as the inner environment, and the craft's material and the craftsperson's habitat as the outer environment. This interface is built upon the assemblage of pertinent disciplines (e.g., computational method, perceptual system) and the evolving knowledge based on the researcher's experience at the site; to reason clearly about the tacit knowledge on the site, I rely upon the explicit representation of my own experience.

In this study, I tweaked the term *ethnocomputing*, described above, to *EthnoComputation* to stress the significance of 'ethnos' in positioning humans at the center of the subject and 'computation' to emphasize the need for explicit and generative analysis. The scope of EthnoComputation in this study is conceptualized as follows:

1. To contextualize a computational framework supported by pertinent disciplines to observe artifacts and human activities on a field study.
2. To interpret physical and perceptual shapes through the interactions between humans and their artifacts.
3. To develop forms of interpretative computational knowledge unique to a particular site and individuals, at a particular point in time.

Thus, the hypothetical reconstruction of craft study in the EthnoComputation method is not archeological or historical; the goal is not to authenticate the craft object. The engagement with the participant on the site is not anthropological or psychological; the goal is not to verify the craftsperson's thinking process or his/her world-view. The way the subject is observed may be

[75] "SmartBird," accessed May 16, 2014, http://www.festo.com/cms/en_corp/11369.htm.

similar to the methods used in these disciplines. However, the research focus is different. The research focuses on the interaction between human and craft because in EthnoComputation, the explicit representation from this interaction *is* the artifact.

Situating the Computational Framework

The computational method for observing traditional contexts must be intuitive (i.e., easy to use in a traditional site) and adaptive so as to anticipate possible emergent interpretations of the site. The method must accommodate both physical and perceptual experience to enable the observers to observe how humans perceive the object. Furthermore, the computational method should not intrude upon the research subject.

To meet these requirements, the study uses Shape Grammar, a computational method used to analyze and synthesize design with a set of shape rules, as the foundation of the research method.[76] Shape Grammar accommodates the above requirements with its intuitive and explicit reasoning process.[77] The simplicity of Shape Grammar rules and the fact that it uses shapes to analyze objects makes it more practical for both interpretation of the subject on the site and knowledge representation for the reader. In addition, Shape Grammar computation does not depend on a particular technology or media, as shape rules can be computed in both analog and digital media.[78] All of these features adapt well to the conditions in a traditional context. To obtain the optimal benefit from Shape Grammar, I contextualize some principles in Shape Grammar for *in situ* application.

First, I present the mathematical abstraction of the Algebra of Shape in Shape Grammar as a perceptual-physical abstraction (Figure 9). In the algebra of shape, the shape is represented as a point, line, plane or solid in n-dimensional

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[76] See the introduction chapter for Shape Grammar definition (page 22)

[77] Terry Knight and George Stiny, "Classical and Non-Classical Computation," *Arq: Architectural Research Quarterly* 5, no. 04 (2001): 355–72, doi:10.1017/S1359135502001410.

[78] See the first shape grammar computation with non-digital representation in Stiny and Gips (1971) and some examples of Shape Grammar digital interpreter by Andrew Li from http://andrew.li and Miranda McGill from http://designmasala.com/portfolio/ui_shaper2d.html.

space (i.e., 0D, 1D, 2D, and 3D).[79] However, the shape and space relationship on a site is represented, not mathematically, but perceptually, relative to the eyes of the beholder. Although object and space in an *in situ* observation are always three-dimensional, that does not necessarily mean the shapes on the site cannot be perceived as two- or one-dimensional representations. Therefore, in this observation, a shape is represented by how its characteristics are perceived (e.g., atomic, linear, planar and volumetric), where the space is represented as a medium that the shape inhabits.

	0: atomic	1: linear	2: planar	3: volumetric
0: atomic	U_{00}	U_{01}	U_{02}	U_{03}
1: linear		U_{11}	U_{12}	U_{13}
2: planar			U_{22}	U_{23}
3: volumetric				U_{33}

Figure 9. Algebra of Perceptual Shape
Based on Stiny's Algebra of Shape,[80] a number in a column represents the dimension of the *perceived space* which a shape inhabits, while number in a row represents the dimension of the *perceptual shape* that exists in the perceived space. For example, U_{12} indicates a linear shape in the planar space. U_{01} is atomic shape in linear space, thus can only do linear motions in an axis (Atomic shape is a type of singular shape that is perceived as not decomposable into smaller parts, regardless of its dimension).

A set of objects -- for example, a pencil resting on a table -- can serve either as a shape or a space based on how an individual perceives the relationship between the pencil and the table. The pencil on the table can be perceived as a one-dimensional line on a two-dimensional plane (U_{12}), yet the eraser surface on the end of the pencil can be regarded as a two-dimensional circle inhabiting a three-dimensional cylinder (U_{23}). Later, if an individual uses the pencil to write or draw, he/she may perceive the graphite tip of the pencil as an end-point of a line-stroke on the paper (U_{02}), or, as a peak point of the graphite cones of the pencil (U_{03}). The former may be more apparent visually (as perceived by the eyes), and

[79] George Stiny, *Shape: Talking about Seeing and Doing* (The MIT Press, 2008).
[80] Ibid.

the latter may be more apparent tactilely (as perceived by a sense of touch via sensory nerves in the fingertips, fingers, hand). Thus, our perceptual mechanisms (visual and tactile) can readily shift the shape–space relationship.

Second, I make an adjustment to situate Shape Grammar rules in order to observe the site. In a rule notation, the shapes are placed on the left-hand side of the arrow (LH-shape) and on the right-hand side of the arrow (RH-shape), where the RH-shape substitutes for the LH-shape (Figure 10). Although the RH-shape sometimes appears as the transformed LH-shape, this does not mean that the RH-shape is always related to the LH-shape. The RH-shape can be anything, including empty space or an empty element. Therefore, any object on the site can be regarded as the LH-shape as well as a RH-shape.

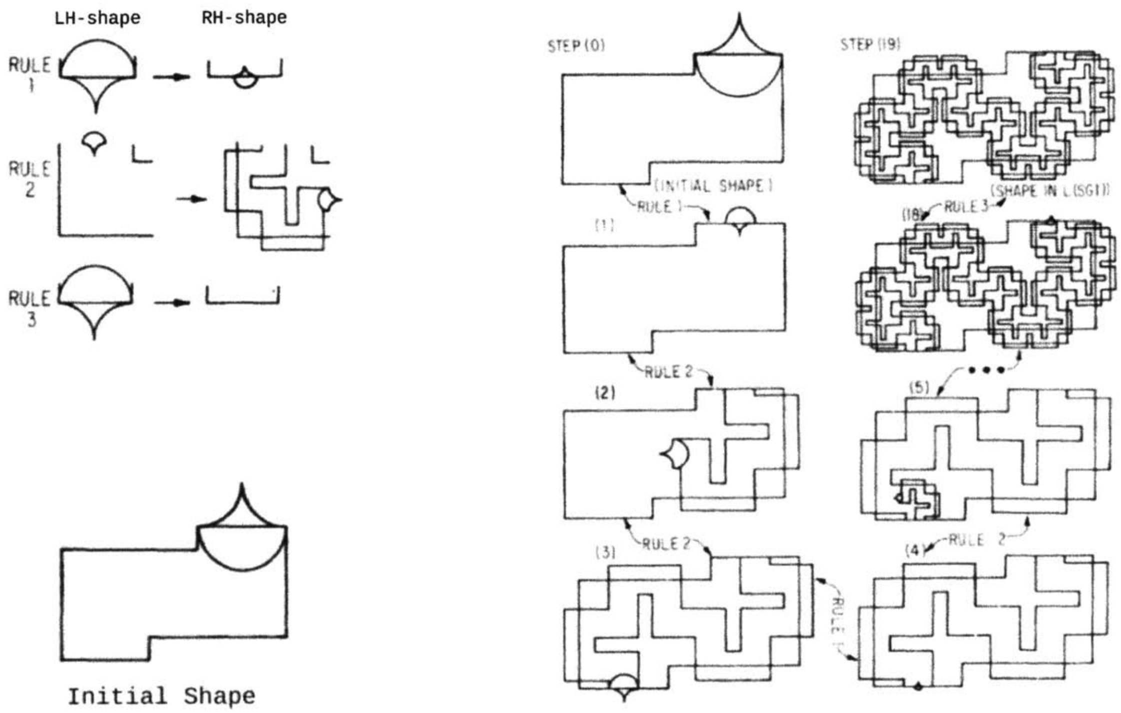

Figure 10. Rules and Computation in Shape Grammar [81]
With three rules on the upper left and the initial shape on the lower left, the computation process on the right shows how rule iterations generate new shapes whenever there is a shape that matches with the left-side shape of rules 1 and 2. Rule 3 will erase the label (teardrop-shape) and stop the computation process because when the label disappears; there will be no more shapes that match with the rules.

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[81] From: George Stiny and James Gips, "Shape Grammars and the Generative Specification of Painting and Sculpture," in *Information Processing 71* (presented at the International Federation for Information Processing (IFIP), Ljubljana, Yugoslavia, 1971).

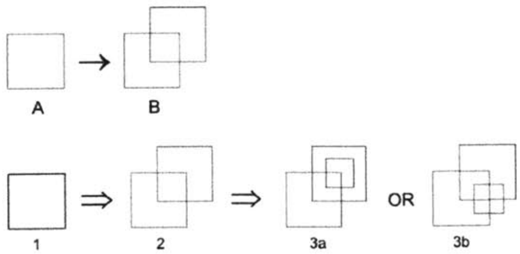

Figure 11. Rules A → B and Computation [82]

In a rule A → B, the arrow does not refer to a particular transformation method for changing the initial shape A into the new shape B. The process of "making a shape" in Shape Grammar computation is quite distinctive, that is: to see A, erase A and show B.[83] For example, consider the shape rule that turns shape A into shape B, and the three iterative steps in Figure 11. Between these steps, more steps are required to make the shape. In *Shape*, Stiny states the procedure to apply the rules:

> ***Find*** *a transformation t that* ***makes*** *the shape A part of C. This* ***picks out*** *some part of C that looks like A*
>
> ***Subtracts*** *the transformation of A from C, and then* ***add*** *the same transformation of the shape B. This* ***replaces*** *the part of C that's like A with another part that looks like B.* [84]

Based on this instruction, the three iterative steps can be extended into six steps in Figure 12, to ensure that the rule is properly applied.

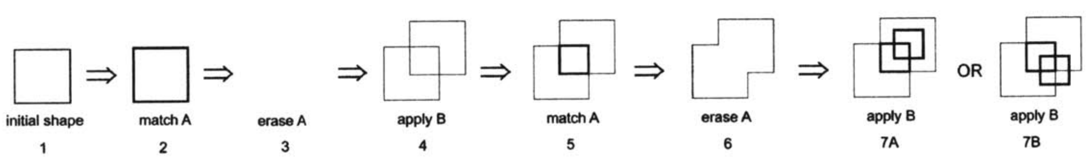

Figure 12. Extended Rules Iteration [85]

The single-lined arrow (→) in the rule is, therefore, open for interpretation as it is up to the rule user to employ the necessary transformation

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[82] Find more example of this shape-rule in Stiny, *Shape.*
[83] Stiny, *Shape.* p:232
[84] Ibid.
[85] Find more example about seeing and doing in Terry Knight and George Stiny, "Making Grammar: From Computing with Shapes to Computing with Things," in *Computational Making* (presented at The 6th International Conference on Design Computing and Cognition - DCC'14, London, 2014).

to *subtract, add* and *replace* in Stiny's instruction. For example, adding a shape in different orientation will result in different designs (see two possible orientations at step 7A and 7B in Figure 12).

Double arrows (⇒) in the rule iteration signify the process of applying a rule (*r*) for a shape *(x)* in an iterative computation r(x). Thus, an iterative computation r(x) implies that rule(*r*) and shape (*x*) exist. By reversing this procedure, in a condition where craft objects exist on the site, we can apply an inverse computation by assuming the existing crafts as the iterative computation to retrieve back the rule (r) and the shape (x).

```
IF (r) AND (x) exist THEN          IF r(x) exists THEN
compute r(x)                       return (x) AND return (r)
```

The return function to retrieve the rule (r) and the shape (x) is interpretative because many rules and shapes can produce the same result(s). Just as embedding the shapes from the shape rule into shape computation can be ambiguous, likewise, embedding the shapes from shape computation into shape rules can also be indefinite.[86]

In a traditional culture, most of which consists of tacitly passed-down traditions, access to explicit representation of the rule is not always direct. For instance, suppose a craftsperson uses the rule in Figure 11 and uses shape B as the initial shape to generate a set of craft objects (Figure 13-1). Later on, if an observer happens to have access to these craft objects but not to the craftsperson's rule, there is no guarantee that the observer will retrieve the rule in Figure 11 (Figure 13-2). Each of the possible embedded sub-shapes in the craft objects could be the result of a different rule interpretation, because each embedded shape can be used to deduce rules. For instance, based on different observations of the embedded shapes in Figure 13-2, different rules (i.e. R2, R3, and R4) can be defined to interpret how a craftsperson generates the craft object in Figure 13-3 and 13-4.

[86] Terry Knight, "Computing with Ambiguity," *Environment and Planning B: Planning and Design* 30, no. 2 (2003): 165–80, doi:10.1068/b12915.

Given the many possible defining rules from the available object-craft on the site, it would be irrelevant to claim the original shape rule, even if a (set of) rule(s) could generate an object that resembles the original craft.[87]

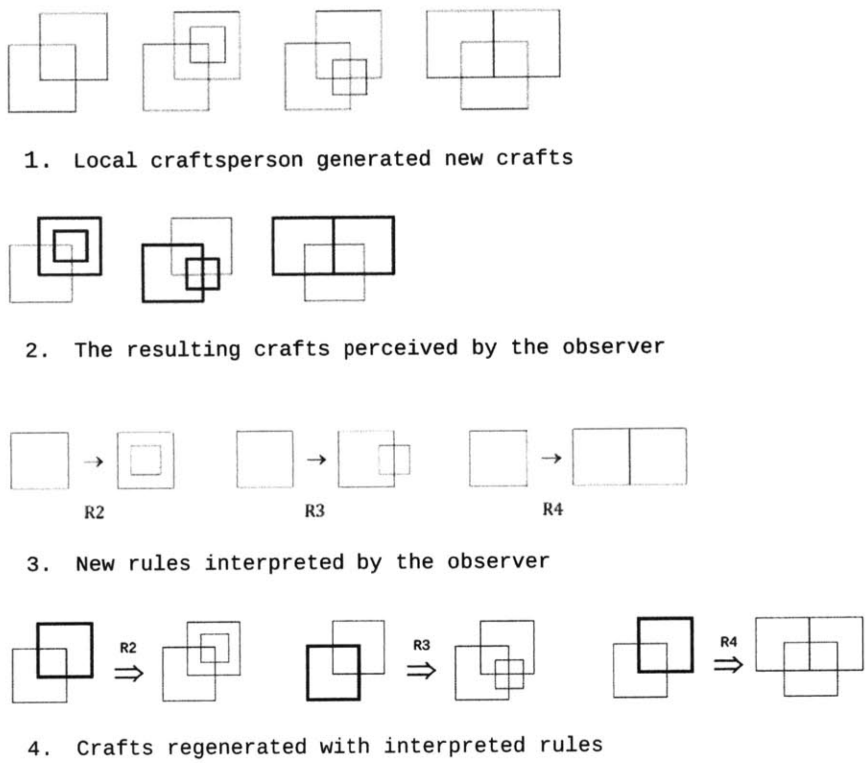

Figure 13. Inverse-computation from existing shapes into interpretive rules

[87] Other constraints, such as crafting skills, could greatly vary the craft objects. If a physical constraint is included in the computation process then the possibility to retrieve the original rules will vastly increase. Assuming craftsperson A and craftsperson B are working with the same rule and the same initial shape, the resulting designs can look somewhat alike but can vary based the physiological differences in the individuals. For example, craftspeople A and B may have different levels of tactile perception in their fingertips and/or different visual perceptions that could lead to different designs based on the same rule.

2.3 Seeing-in-There

Figure 14. Kete Kesu, Toraja, Indonesia

The region of Toraja, Indonesia is well known for its ornamental crafts, woodcarvings, unique traditional houses (known as *Tongkonan),* funeral rituals and other traditional ceremonies.[88] [89] [90] The site location, Kete Kesu, is a village in Toraja of about 350 residents. Culture in the village embraces a wide range of craft diversity. There is an abundance of interwoven artifacts and weaving materials (bamboo) around the village. Interwoven bamboo is commonly used to craft household items such as chicken cages, carriers, sacks, room and building partitions, and decorative hangings.

Site as a Schema

Figure 15. The initial setting for EthnoComputation

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[88] Kathleen M. Adams, *Art as Politics: Re-Crafting Identities, Tourism, and Power in Tana Toraja, Indonesia* (Honolulu: University of Hawaii Press, 2006).
[89] Jowa Imre Kis-Jovak, *Banua Toraja: Changing Patterns in Architecture and Symbolism Among the Sa'dan Toraja, Sulawesi, Indonesia* (Amsterdam: Royal Tropical Institute, 1988).
[90] Roxana Waterson, *Paths and Rivers: Sa'dan Toraja Society in Transformation* (Leiden: KITLV Press, 2009).

Just as there are different ways to see a shape, there are different ways to perceive a site. I represent the setting in Figure 15 in a non-judgmental view where all objects on the site are recognized as shapes that hold equal Weight.[91] For instance, objects in the foreground, mid-ground and background have the same level of hierarchy (the person is no more important than the other objects or vice-versa). The non-judgmental view is analogous to an "image processing framework", proposed by David Marr in computer vision. In Marr's framework, retinal image, a representation of object in the real world that is projected into a retina, has no meaning attached. A retinal image is processed through a bottom-up approach from low-level vision (differentiating edges of one object with another), to mid-level vision (recognizing shape attributes such as color, shading, texture, motion flow), and then to shape recognition in a high-level vision, where shape attributes from mid-level vision is being recognized with meaning.[92]

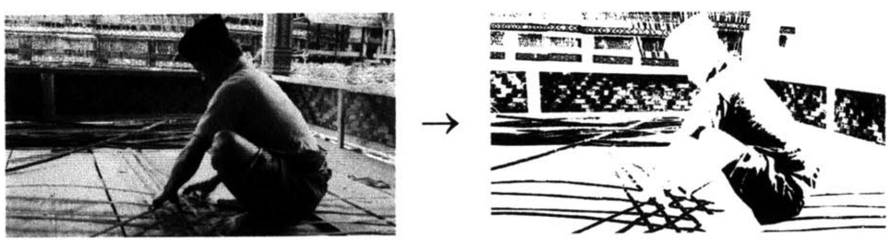

Figure 16. The initial setting (left) is weighted with a term 'weave' to highlight woven shapes on the site (right).

In this setting, I only recognize objects in their basic terms (e.g., a person, threads, a panel), but their value and their relationship to another are neutralized. This non-judgmental view serves as my initial setting to compute my research focus on the site. In this setting, I begin to add Weight to the shapes that match the description of 'weave' as a cyclical over-and-under shape relationship, such that: IF weave is found THEN adds Weight to the weave. The Weight will contrast weave apart from other objects on the site, and gradually, only parts considered as woven are perceived in this scene, e.g., woven-partition, woven basket-base, woven screen, etc. (see Figure 16).

[91] G. Stiny, "Weights," *Environment and Planning B: Planning and Design* 19, no. 4 (1992): 413–30, doi:10.1068/b190413.

[92] (David Marr, Shimon Ullman, and Tomaso A. Poggio, *Vision: A Computational Investigation into the Human Representation and Processing of Visual Information* (MIT Press, 2010).

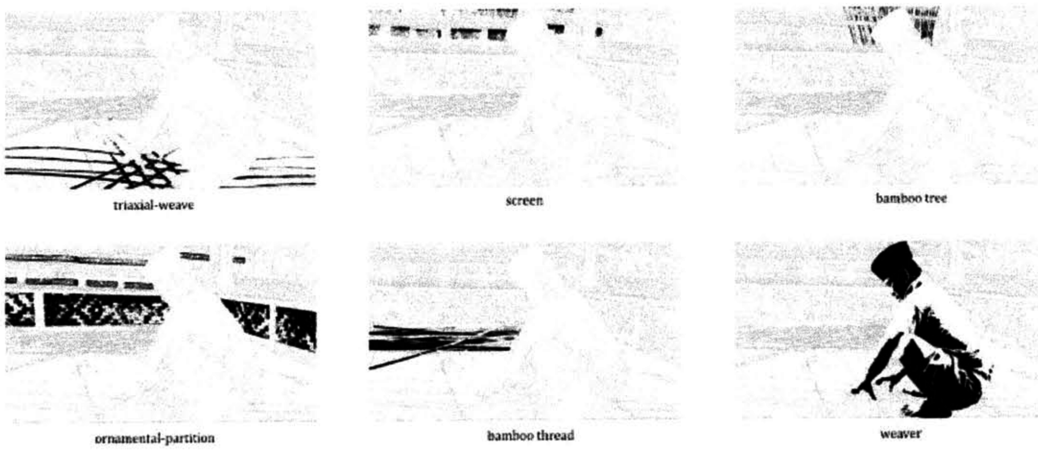

Figure 17. Weighted objects on the Site
Weight highlights shape related to weaving in its particular form, e.g. ornamental partition and screen, triaxial-weave, bamboo thread and bamboo tree as a weaving material, and the weaver.

Reconfigured Sites

Objects in the setting are recognized separately in the weighted site as their relationship is not yet defined (Figure 17). This setting serves as a schema that can generate emergent research frameworks for perceiving the site. For example, in the site schema, an observer might recognize ornamental shapes on the interwoven partition in the background and further investigate differences between weaving for ornamental and weaving for practical purposes. The emergent relationship between the weaver and the ornament in Figure 18 shows one of many possible frameworks that can be generated from the site schema.

For this study, I limit my scope to weaving in two frameworks (Figure 19). The first framework highlights the transformation of weaving material from nature into craft components, given the ubiquitous bamboo trees in the background and the pervasive interwoven bamboo artifacts in the setting. The second framework focuses on the weaver's interaction with the weave during the production process, given the weaver's constant visual and physical focus on the material.

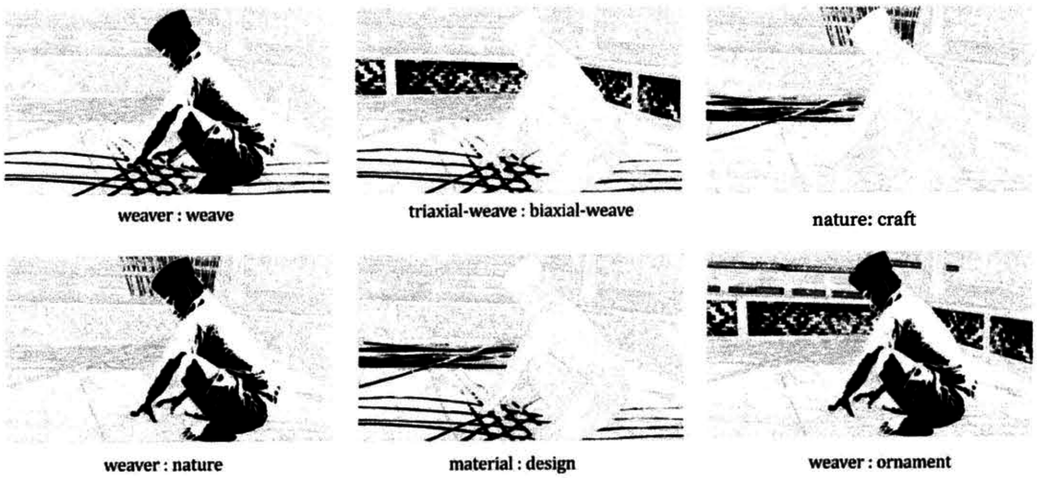

Figure 18. Object associations
Objects in the setting are paired to generate different frameworks in perceiving the site.

Figure 19. Reconfigured Sites from Object Association: Nature-Craft and Human-Craft
Two frameworks from object association highlight my research focus on the site: [1] How nature is transformed into material, and [2] how material is transformed into a design by the weaver.

2.4 Mediated Bamboo

This section illustrates my observations on bamboo as the weaving material by focusing on the way that bamboo's shape is transformed from matter (nature), into form (craft).

In view of the dominance of form in the form and matter relationship, Tim Ingold, anthropologist, proposes an alternative model to Aristotle's *Hylomorphism*. Ingold criticizes means of reproduction that occur between the conception of a material as a "formless lump of matter" and the material as "form-bestowing agency of human beings".[93] [94] Building upon philosophers Gilles Deleuze and Félix Guattari's model, *Matter-Flow,* Ingold renders his *Environment Without Object (EWO)* model, where matter flows through the physical environment. Thus, even in its 'brute' form and in the absence of human agency, material is always in a state of flux, changing as it interacts with its environment.[95] [96] [97]

Ingold's EWO model supports my aim in investigating the flux of shapes in bamboo's transformation. Yet, in spite of Ingold's criticisms of Hylomorphism, the theory of four causalities (a theory embedded in Aristotle's Hylomorphism model) provides checkpoints that could help to navigate the flows of the shape. The four causalities in this theory are the *material* cause (that from which something is generated and out of which it is made); *formal* cause (the structure in which the matter comes to be something determinate); *efficient* cause (the agent responsible for a quantity of a particular matter that is formed) and *final* cause (the purpose or goal of the object created from form + matter).[98] In my case, the efficient-cause is represented by the weaver; the material-cause is represented by

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[93] Tim Ingold, *Bringing Things Back to Life: Creative Entanglements in a World of Materials*, Working Paper (Realities / Morgan Centre, University of Manchester, July 20, 2010), http://www.manchester.ac.uk/realities/publications/workingpapers/.
[94] Hylomorphism (matter: *hulê* and form: eidos or *morphê*) holds that no such object contains two distinct metaphysical elements: one formal and one material.(Shields, "Aristotle.")
[95] Based on James Elkins, *What Painting Is*, 1 edition (Routledge, 2004).
[96] Tim Ingold, *Making: Anthropology, Archaeology, Art and Architecture* (Routledge, 2013).
[97] Tim Ingold, "Of Blocks and Knots: Architecture as Weaving," accessed May 17, 2014, http://www.architectural-review.com/comment-and-opinion/of-blocks-and-knots-architecture-as-weaving/8653693.article.
[98] Shields, "Aristotle."

the bamboo; formal-cause is represented by the basket; and final-cause is represented as the carrier.[99]

Responding to Ingold's EWO and Aristotle's theory of causation, in observing bamboo as a local weaving material, my observation is situated at the flows *in-between* these causalities. Therefore, an initial mapping of these causalities -- for instance, in basket weave, "a basket is made by linear thread and woven into a cylindrical shape by a weaver to be used as a container to carry things," -- is not perceived as the final explanation. Rather, it is an interface to understand how the four causes affect one another.

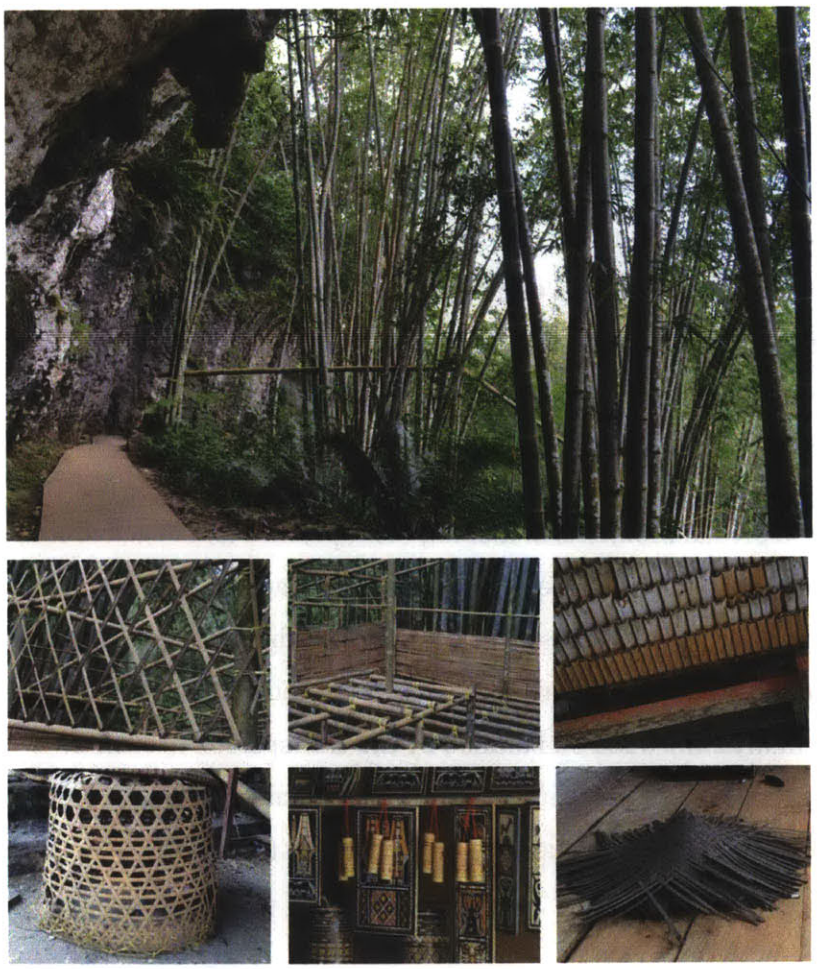

Figure 20. Abundant Bamboo trees (top) and various bamboo crafts in Kete Kesu (bottom)

[99] Anna Marmodoro, "Aristotle's Hylomorphism without Reconditioning," accessed May 17, 2014, https://www.academia.edu/4195031/Aristotles_hylomorphism_without_reconditioning.

I investigate the dynamic of these causal interactions in different materialization states. I begin from a state where the bamboo tree is considered matter and the pole of the bamboo is form, and then moving to the state where the pole is considered matter and the thread, form, and later on in the process, to a state where the thread is matter and the completed basket, a form.

In each of these recursive states, I focus at the moment when the craftsperson perceptually gives form to the matter. In particular, the moment when s/he visualizes the desired shape, right before his/her physical action is applied to the matter. In cutting down the tree, for example, when a logger swings his axe to cut the tree, he may visualize a shape on the tree as a target area for the axe in order to properly hit the tree.

Generative Bamboo [100]

The wide range of bamboo crafts in the village can be represented with a parametric schema. In this schema, the part of the bamboo that is cut off (negative shape) and the part that is uncut (positive shape) are equal. For instance, a rectangular shape appears in the bamboo crafts, both as a positive shape (i.e., a rectangle as a two-dimensional projection of the cylindrical bamboo) and as a negative shape (i.e., rectangular holes in bamboo).

One of the pivotal moments in making these positive and negative shapes occurs when the craftsperson's knife-edge comes in contact with the bamboo surface to cut it into different shapes. This contact links the inner environment of the craftsperson, and the outer environment of the bamboo. Therefore, the knife's cutting line, mentally embedded on bamboo by the craftsperson in such a moment, can be regarded as an interface with which to interpret the craftsperson's knowledge and the bamboo-craft diversity (Figure 21).

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[100] Klaus Dunkelberg, *IL 31, Bambus. IL 31, Bamboo. Bambus Als Baustoff. Bauen Mit Pflanzlichen Stäben.* (Krämer, Stuttgart, 2000). Provide numerous detail on bamboo utilization in Indonesia, including Toraja, which has been used as a main reference in this study along with my direct observation on the site.

Figure 21. Bamboo-Cutting Line
Weaver cutting-bamboo activity as the interface and the embedded mental-shape as the artifact for ethnocomputation study. Contact area between the knife-edge and the bamboo is represented with the cutting shape (red line), as an interface between the craftsperson's inner-environment and his outer-environment.

Based on the weaver's cutting bamboo activity as the interface, I describe my interpretation of the cutting process using two representations of bamboo: a side-elevation and a cross-sectional view.

Side-Elevation Rules

The cylindrical shape of the bamboo pole is represented through the bamboo's side elevation with two cutting rules: longitudinal cut and lateral cut. The distance between the end of the pole and the cutting line is parameterized with variables: length (L) and width (w) (See rule R1 and R2 in Figure 22). The two cutting rules can be applied recursively to generate more cutting lines, in order to subtract the bamboo. After the cutting rule is applied, the desired shape can be signified with Weight by applying rule R3. The three examples of rule R3 application indicate different desired shapes from the same cutting lines.

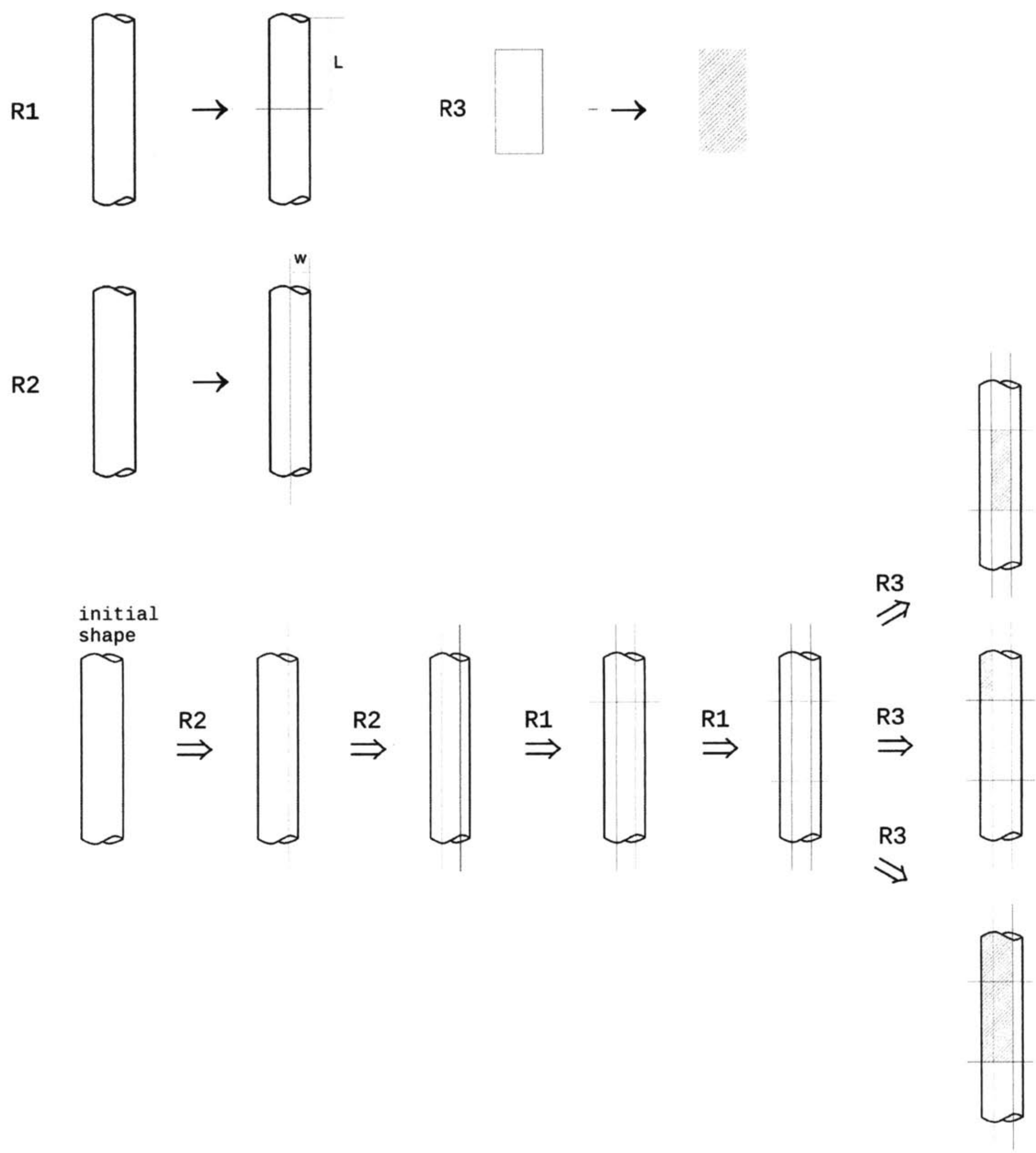

Figure 22. Cutting rules on the surface
Two parametric rules (R1: axial and R2: longitudinal) add cutting line to bamboo with a distance variable (L and W). The rules can be applied recursively to generate several cutting lines (e.g. R2-R2-R1-R1). Within these cutting lines, two-dimensional weights (shading) from rule R3 will mark the desired shape for the subtraction. Note that the grain direction of the bamboo, which runs parallel to its longitudinal axis, would make it easier for the craftsperson to cut the bamboo using rule R2, as forces from the knife would traverse easily along the grains direction.[102] [103]

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[102] See more about grain property of Bamboo in Dunkelberg, *IL 31, Bambus. IL 31, Bamboo. Bambus Als Baustoff. Bauen Mit Pflanzlichen Stäben.*

The form of knowledge in interpreting the cutting process with these rules can be accumulated into a lattice of rule iterations. The lattice diagram in Figure 23 illustrates a bamboo derivation from nature to several craft components. The two ends of the diagram represent the original bamboo pole, one projected as a two-dimensional shape at the top and the other as a three-dimensional object at the bottom. In between, the rule iteration guides the process from one step to the next. An observer who sees bamboo as part of nature on the site can use the lattice to interpret how craftspeople transform the natural object (the bamboo pole) into various crafts components and utilitarian objects based on the cutting rules in Figure 22.

Or, the other way around, an observer viewing the finished craft component can interpret how craftspeople made it from a bamboo pole. Given existing bamboo crafts, an observer can trace the shape, beginning at the subtracted shape at the bottom part of the diagram, back to the top of the diagram (the original bamboo pole).

[103] In addition, a desired shape can also be predefined and embedded in the surface at the beginning as the initial shapes indicate the cutting lines.

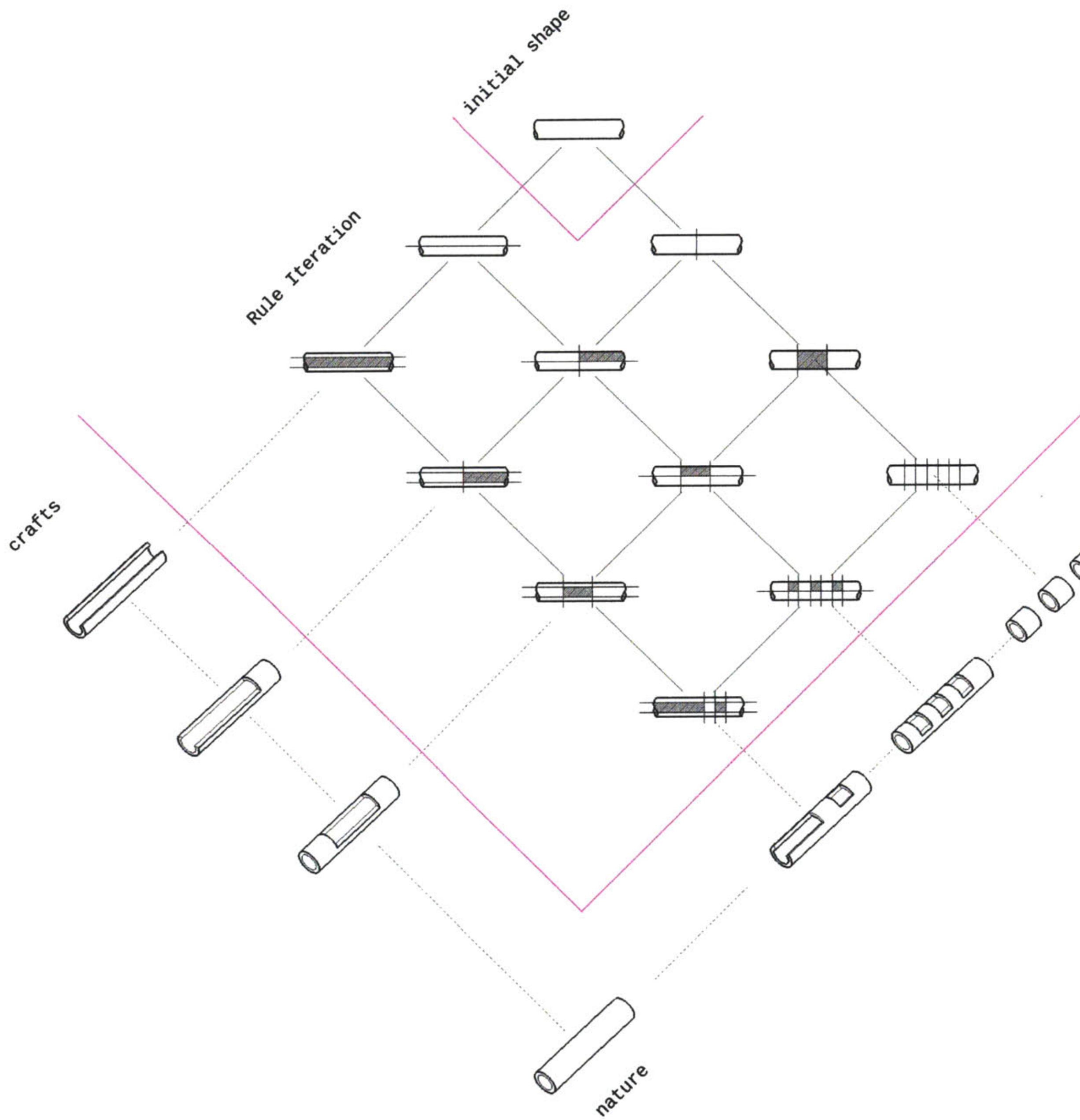

Figure 23. Lattice of Cutting Rules on Bamboo surface

Using planetary pole analogy, two poles of the lattice represent the original bamboo from nature in two projections, two-dimensional (top) and three-dimensional (bottom). Between the two poles is the computation, using the rules in Figure 22. Moving to the left-bound, cutting lines are generated using rule R2 (longitudinal) recursively. Moving to the right-bound, the cutting lines are rule R1 (axial) iteration. The iteration in the middle indicates the use of two rules simultaneously in particular sequences (e.g. R1-R2-R1 or R1-R1-R2). Shading in each shape indicates the desired area for subtracting the bamboo. At the end of the iteration are the subtracted shapes in three-dimensional form. One who sees a similar artifact to these shapes can interpret how the shape is made by navigating the lattice back to the top. One who wonders how the bamboo is derived into various crafts can start navigating from the top and go downwards.

Cross Section View

In addition to the bamboo side elevation, the observer can embed the cutting lines from the bamboo's cross section. After the pole is cut, an observer can see an emergent circular shape. Here, the cutting rules are parameterized based on the knife's position on the surface-edge of the bamboo (cross section). The examples in Figure 24 show two schemas to place the knife's blade on the cross-sectional profile (rule R5 and R6). Relative to the profile's center point, rule R5 translates the knife parallel with the bamboo's profile diameter within a distance (D) while rule R6 angles out the knife blade from the center by a certain number of degrees (α).

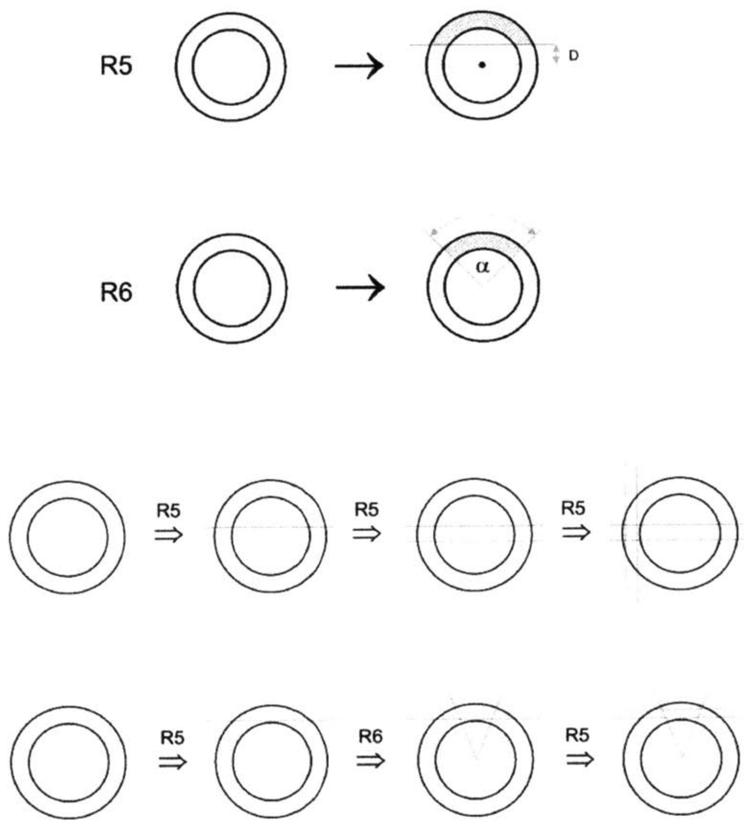

Figure 24. Cutting rules on cross-sectional profile
Two parametric rules place a knife in the cross-sectional view of the bamboo within translation variation (D) in rule R5 and angular variation (α) in rule R6. The rules can be applied repeatedly, as shown in the first computation (e.g., R5-R5-R5) or shifting back and forth between the two rules in the second computation (e.g., R5-R6-R5). Note that the infinite order of symmetry of the circle allows a user to apply the rule in infinite ways.

Rule R5 and R6 (Figure 24) are parametric. They can be applied individually and also in combination with each another. The infinite orders of symmetry of the bamboo profile (i.e., the circle) provide many ways to match the initial shape in each step. The cutting lines outlined in rule R5 can be placed at different angles, as any angle will always match the circle. The first iteration shows a rule (R5) applied recursively in the computation. The second iteration shows a combination between the two rules (R5 and R6) of cutting lines.

The newly-constructed profiles from the rule iteration generate many types of bamboo threads. The form of knowledge in interpreting the making of threads from bamboo is represented with a lattice in Figure 25. The lattice shows different approaches to placing and angling a knife. At the top of the diagram is the profile's two-dimensional projection and at the bottom is the three-dimensional bamboo pole. Shapes in between the top and the bottom show parametric rule iteration. In this iteration, the left-side iteration shows how the bamboo profile would look if rule R5 were applied recursively and the right-side iteration shows how the range of parametric variations of rule R6 would change the profile. For example, if the bamboo profile is cut with lines shifted away from the center (R5), the shape is generated in the left bound direction on the diagram. Similarly, if the profile cut with an angle (R6), the shape is generated in the right bound direction. If the iteration turns into the different direction, it means two rules are being used simultaneously.

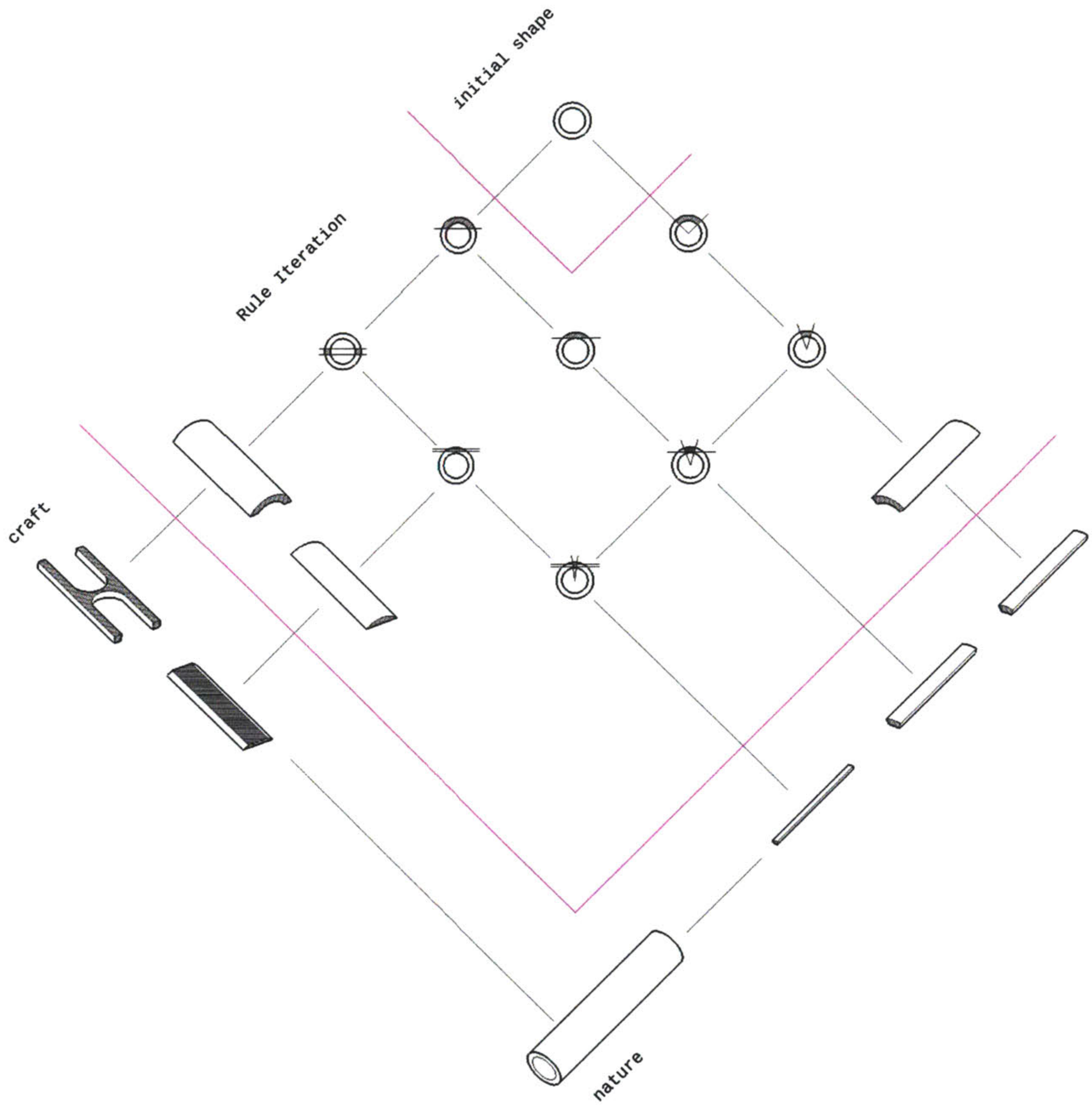

Figure 25. Lattice of Cutting Rules on Bamboo Cross-Section
The two poles in the lattice represent the original bamboo from nature in two projections, cross-sectional view (top) and three-dimensional view (bottom). Between the two poles is the computation using the rules in Figure 24. Toward the left-bound, cutting lines are generated using rule R5 (translational) recursively. Toward the right-bound, the lattice shows rule R6 (angular) iteration. The iteration in the middle indicates the use of two rules simultaneously in particular sequences. Shading in each shape indicates the desired area for subtracting the bamboo. At the bottom sides of the lattice are the subtracted shapes in three-dimensional form. Note the size of the bamboo profile becomes finer and thinner as the rule is applied repeatedly toward each bound.

Reciprocal Causality in Indigenous Materiality

In the previous section, I have described the role of bamboo as a weaving material in the traditional village through computational design interpretation. Findings from my EthnoComputation observation are reported with interpretive shape-rules to describe, explicitly, how matter is translated into form. In these interpretive rules, the dynamics of Aristotle's four causalities recursively shift by their reciprocal relationship from one causality to another. The material-cause (bamboo) provides substance to the efficiency-cause (craftsperson) by which the craftsperson realizes his/her intentions by shaping the material into a new formal-cause (new form). In turn, the new formal-cause provides new final-cause (new purpose), and to derive new purposes, the new formal-cause becomes the new material-cause.

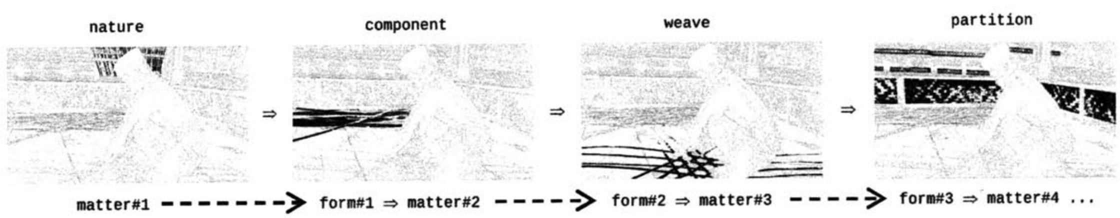

Figure 26. Recursive Causalities

The reciprocal causalities can change the agent or craftsperson's affordance in perceiving matter, form and purpose. Shape polarization from the rule indicates that the craftsperson (the agent) is not always guided visually, but also haptically by the flexible behavior of the material. For instance, bamboo-thread flexibility could expand the vocabulary of form from line to curve, which could eventually extend the agent's function and material vocabulary (e.g. from rigid planar partition into a flexible curvilinear basket).

In this reciprocity, craft variation is not limited to, in Deleuze's words, "*differences in type*", which merely need dimensional manipulation, but also "*differences in kind,*" which show few similarities between one and another, as exhibited in various forms of bamboo crafts.[104] [105] We can assume that the vast

[104] Gilles Deleuze, *Bergsonism* (New York: Zone Books, 1988).

[105] Gilles Deleuze, *A Thousand Plateaus: Capitalism and Schizophrenia* (Minneapolis: University of Minnesota Press, 1987).

diversity in bamboo crafts is a result of both different types and different kinds of shapes that are mentally embedded by the craftsperson into the original material.

2.5 The Weaver and the Weave – Sensorial Weaving

In the previous section, I interpreted the way materials are perceived and transformed, from their original form and function in nature to a craft component. The different ways of perceiving the material's origins in nature lead to multiple ways of shaping and crafting the material in Kete Kesu, Toraja. In this section, I illustrate the ways in which material is transformed into weaving through the craftsperson's senses, in particular the senses of vision and touch.

In analyzing craftsperson's senses, I position my EthnoComputation study within the two leading approaches in the "Anthropology of the Senses": [107]

> (1) **Communal sensing versus Personal sensing.** Sensory studies can be situated within the scale of community to represent the way a group's senses symbolize their cultural model, or at the individual scale to analyze human perception as a personal sensing endeavor. In approaching my research subject, my observation leans toward the latter: the weaver's personal sensing experience. While this research acknowledges that the weaver's talent is shared by the other craftspeople in the village, my observation does not attempt to characterize the 'weaving culture in Kete Kesu'.
>
> (2) **Visual perception versus Nonvisual Perception.** Visual dominance has been challenged for being over-studied and overemphasized at the expense of the other senses, such as hearing, taste, and touch.[108] The form of narration in this study relies upon the visualization of shapes as a media to represent the weaver's sensorial experience. However, in this visualization, shape is not exclusively registered to a weaver's visual

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[107] Based on Sarah Pink's *Doing Sensory Ethnography*, who situates several issues in sensory ethnography, by highlighting David Howes's and Tim Ingold's differences in approaching and framing senses of their subject. Sarah Pink, *Doing Sensory Ethnography* (SAGE Publications Ltd, 2012).

[108] In response to this, Howes, for instance in his book "*Aroma*", promotes smell as the dominant sense.[108] Ingold, despite his advocacy of the important of touch,[108] suggests positioning vision as part of *intermodal perception*.

perception, but also to the weaver's haptic perception. In this registration, shape is considered as a medium to represent both stimuli and reaction from the weaver's visual and haptic perception.

Sensorial Computation

The weaver in my field study is a native Toraja man who practices various weaving activities to produce crafts such as hats, partitions, and baskets.[109] For this study, the man was weaving a basket. The basket consisted of 24 bamboo threads woven in the triaxial weaving style (See basket in Figure 20). Figure 2726 represents a process of weaving the basket's base. The process is divided into 24 steps where the iteration is based on the number of threads in each step (from steps 1–13) and the number of sides of a thread that defines the perimeter of the base (from steps 14-18).

This 24-step iteration is a typical representation of the step-by-step instruction format that I mentioned in the introduction.[110] It shows the weave's evolution but not the weaver's interaction with the weave. In particular, not shown here are the weaver's visual attention and the way he touches the threads when making adjustments and correcting mistakes as he weaves. Based on my observation of the weaver-weave interaction, the weaver's fingers, hands, arms, legs, foot, and eyes were actively and simultaneously engaged each time he added and adjusted a new thread on the weave; his entire body was engaged in the process.

This study assumes that shapes the weaver sees and touches in his sensorial interaction embody important aspects of his weaving. To interpret the role of these shapes, in the following, I highlight the interaction that occurred *in between* the 24 steps in more detail. Specifically, I focus on a weaver-weave interaction between the third and fourth steps (marked by the red arrow in Figure 2726), and represent the interaction in a computational iteration. This computational iteration of weaver's seeing and touching activity, hereafter

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[109] Note that in this village, a person's profession is sometimes mixed with his/her other activities. To earn his living, the weaver needs to simultaneously weave as well as work on other jobs, e.g. harvesting, house-construction, etc.
[110] See a step-by-step example in *O Ita Prefecture – Weaving Technique*

referred to as *sensorial computation*, serves as an interface for me to interpret how the weaver perceives the weave.

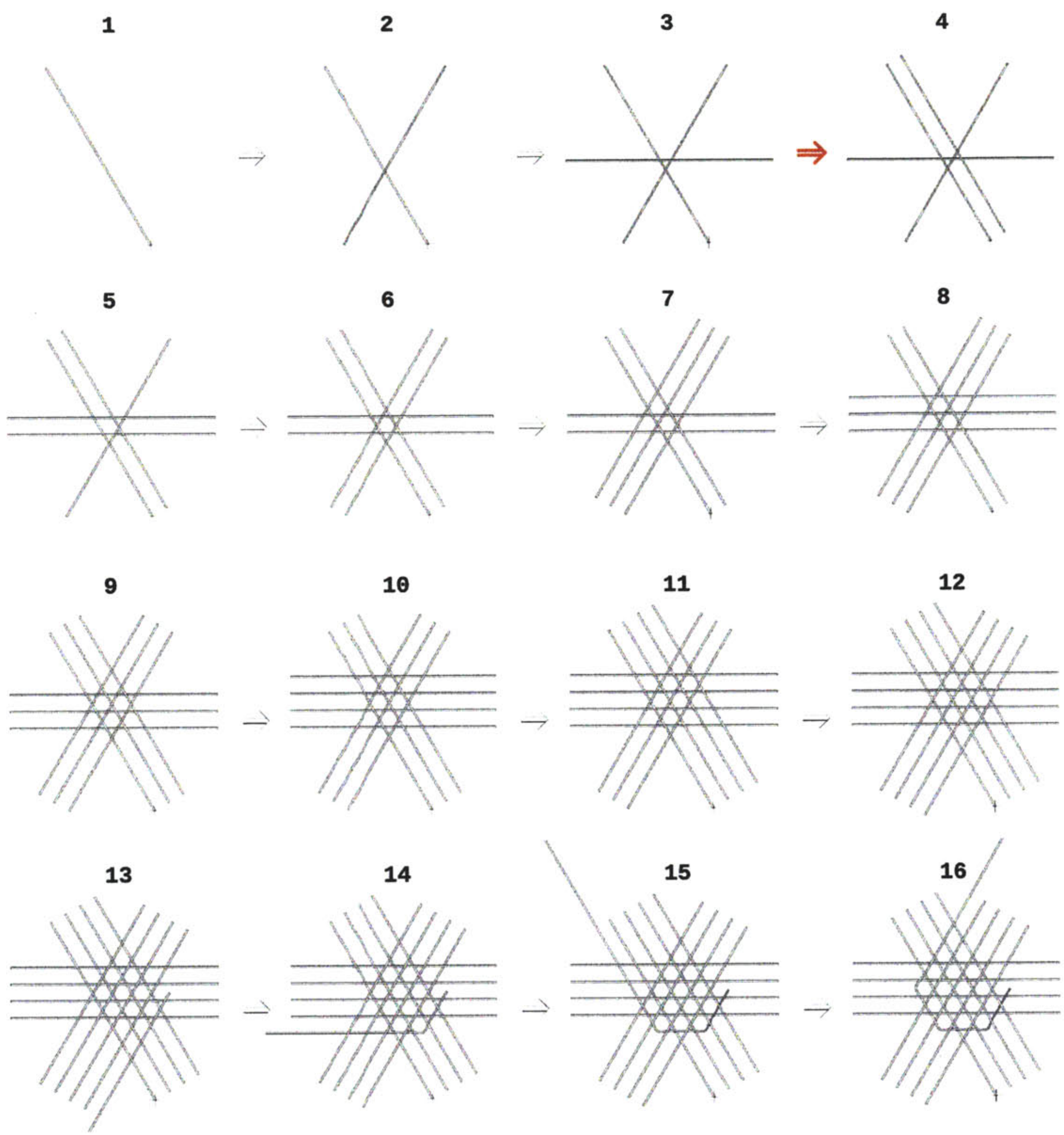

Figure 27. 24 steps iteration in weaving the base of the basket
This step-by-step model is commonly used in weaving instructions, where the continuous process is discretized based on the number of threads, e.g., if the numbers of thread increased, the process translated into one step.

The sensorial computation between the 3rd and 4th steps is discretized based on the weaver's vision and touch. Figure 2827 shows an example of the shape that the weaver sees and touches.

In seeing: the blue color shows shapes from the weaver's visual attention on the threads. This shape is represented in one step. As the weaver shifts his gaze to see a different shape, the new shape would then be added into sensorial computation as another step.

In touching: the red and yellow strips show the area that the weaver touches (red for feet and yellow for hands). The haptic interaction is discretized into one step based on his hands' positions on the thread, and another step if the position of either of his hands changes.

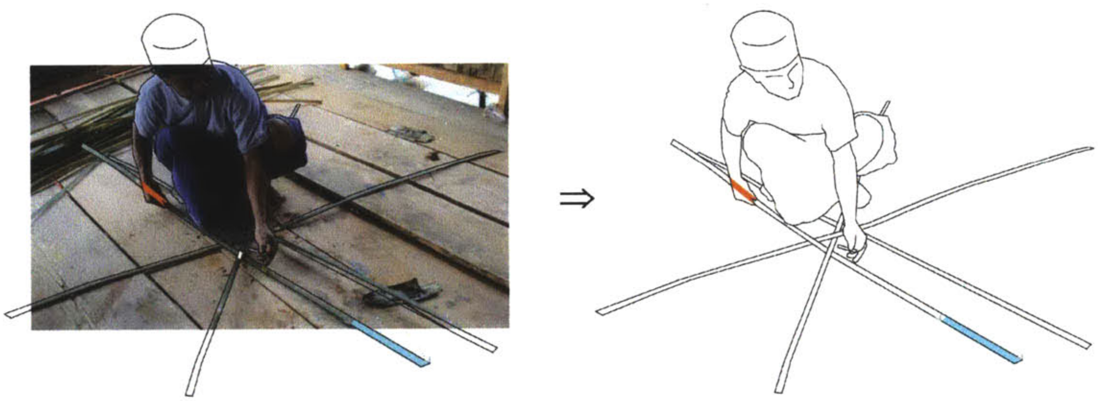

Figure 28. Sensorial Weight
Weaver sensorial interface with the weave is represented with shapes based on his eyesight on the weave (blue) and his hand contact (orange) on the threads.

Based on visual and haptic discretization, the weaver's experience is represented in a sensorial computation in Figure 2928. In the weaver's sensorial computation, the iteration shows eighteen steps between steps 3 and 4. In Figure 2726, eleven steps are shown for vision (first row), and nine steps are shown for touch (second row).

In each step of the sensorial computation, I add labels to indicate a certain weaving condition, such as position of the thread (**pos**), parallel condition between two threads (**prl**), alignment of a thread with other shape (**al**), distance into a specific location (**dis**) and crossing between two threads (**crs**). For each label, the signs (+) and (-) indicate whether the weaver achieved the desired condition (+) or not (-). For example, **prl+** means the shapes are parallel and **prl-** means the threads is unparalleled.

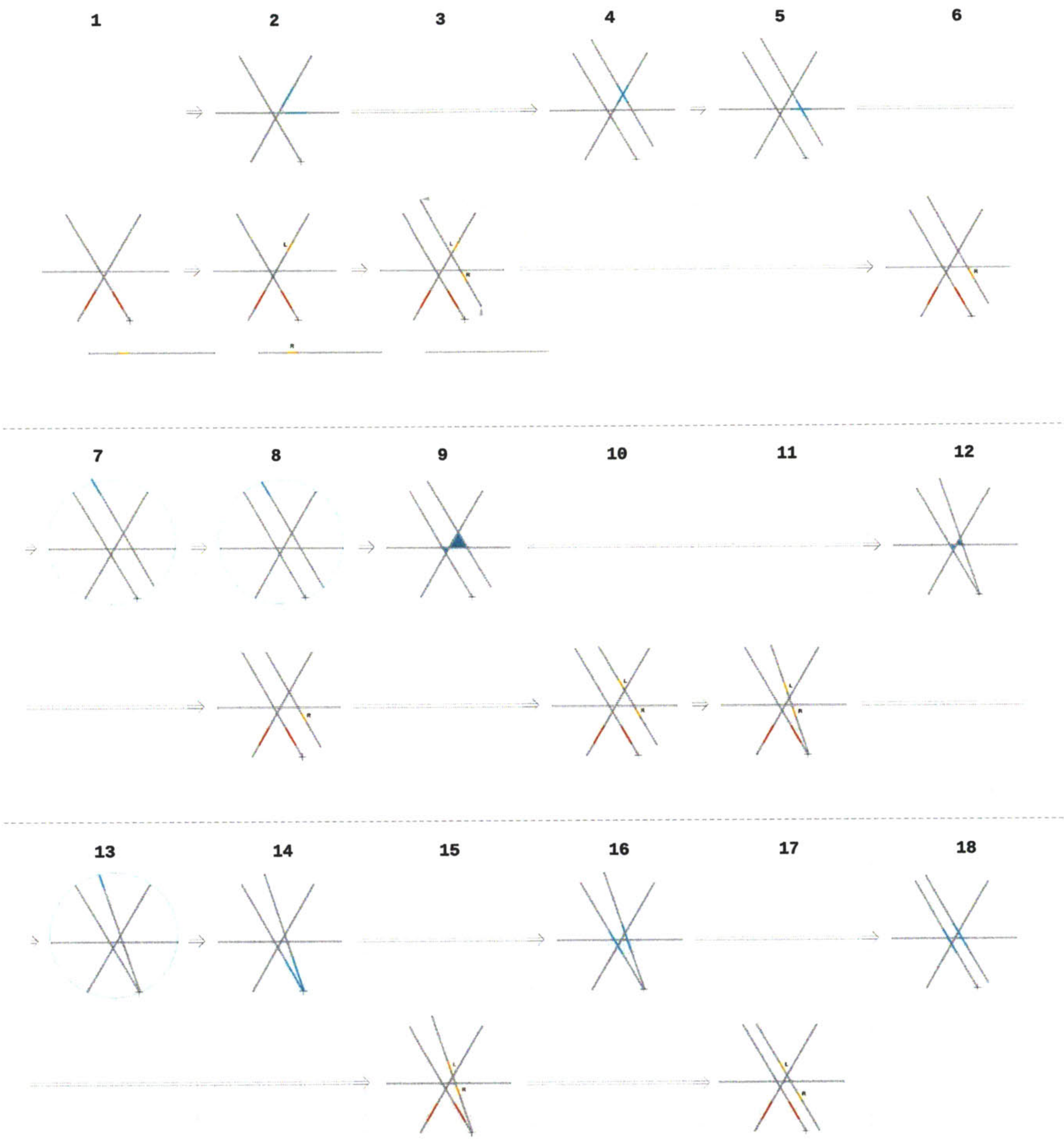

Figure 29. Sensorial Computation
The actual continuous process between step 3 and 4 is discretized based on weaver's sensory attention, i.e., if the weaver changes his visual attention or his hand contact on the thread, I discretize the process as one step. The first row represents the weaver's visual interaction with his weave; the second row represent his tactile interaction (his hand-touch on the threads). The two shapes at the end of the iteration represent the initial and final condition between steps 3 and 4 (see Figure 2726).

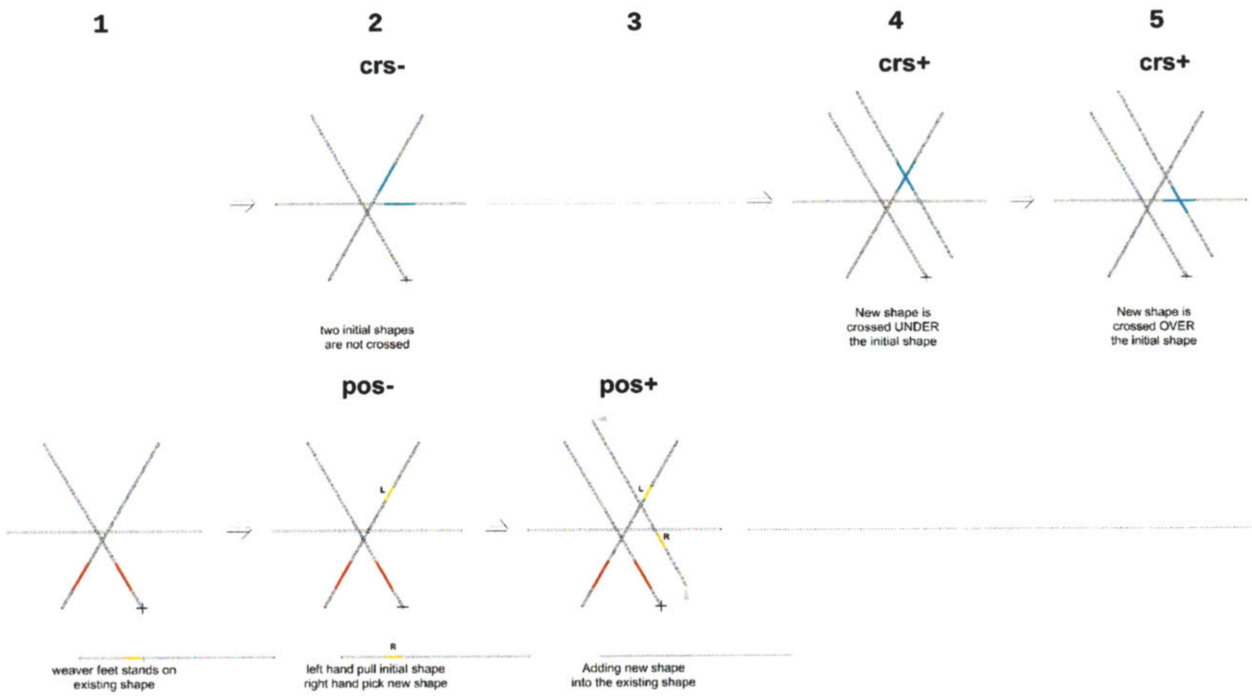

Figure 30. Continuous Attention Span
The weaver's focus on the weave shifts back and forth between visual and haptic sense. The long arrow in the top row indicates the weaver's eyesight continuously fixed at the weave, while his hand adds a new thread to the weave (yellow color in the bottom row). In the subsequent steps, the long arrow in the bottom-row indicates the weaver continuously sensing, his hand on the thread, while his visual attention focuses on the knot condition (blue) (see the label: `crs-` → `crs+`).

The long-dashed arrows (===⇒) that subsume more than one step on the above or below row indicate that the weaver is continuously sensing on that particular row. For instance, in steps 2 to 4 in Figure 3029, while the weaver's hand is adding a new shape in step three in the second row, his visual attention remains focused on the area where he will add the new shape. Therefore, step three in the first row is represented with a dashed arrow. In the second row, another dashed arrow in steps 4 and 5 represents the continuity of the weaver's tactile attention. In these steps, he continuously holds the thread at the same spots while he uses his vision to evaluate whether or not the new and existing threads are crossed into a knot.

Permanency and Temporality in Mental Shapes

Sensorial computation of this weaver highlights some shapes involved in the adjustment of the weave. In representing these shapes, I incorporate information from my interview with the weaver about the basket he is making. As a weaving goal, the basket has a cylinder-shaped dome topped by a circular lid. Thus, to weave a basket properly, the end of each thread should coincide with the circle.

However, in step 7, there seems to be a misalignment between the thread and the circle. To fix this, he pulls his arms back to align the shape and the circle (Figure 3230). In step 8, the labels **dist+** on the second row represent the desired distance to align the thread is achieved, while labels **al+** in the first row confirm the alignment of the thread with the circle. This adjustment implies that as he weaves, he is always considering the final shape.

In addition to the weaver's mental image of the basket-lid as the final form, there is an indication that mental shape is not only embedded in the thread's shape, but also in the space around the threads and in-between each individual thread. In an interview following this observation, I showed the weaver an image of unfinished two-dimensional woven lines and ask him to guess what image it was (Figure 31). The weaver looked at the image carefully but had difficulty identifying this object as a weaving pattern. He guessed that the image was a partition, a road, but not an interwoven pattern.[111] When asked why he did not perceive it as a weaving, he said because it doesn't have a contrast color in the space between the threads. His answer raises an interesting point concerning the attention he pays to the space between the threads while he weaves.[112] In the following, I incorporate this answer in the weaver's sensorial computation.

Figure 31. Ground shapes as mental shape in weaving
The an unfinished three-by-three weaving pattern (left) that was shown to the weaver. To recognize the weaving pattern, he needs to see the shade in between the yarn (middle) to perceive the complete weaving pattern (right).

[111] I also posed this question to other craftspeople on the site, and most of them were able to figure out the weaving pattern in the image.

[112] I have described in more detail about how weaving is visually perceived according to Gestalt Law: see Rizal Muslimin, "Recursive Embedding of Gestalt Laws and Shape Grammar in the Weaving Design Process," vol. 1 (presented at the 30th eCAADe, Prague, Czech Republic, 2012), 443–49. And Rizal Muslimin, "Gestalt Grammar in Weaving Design: Leveraging Visual Affordance in Analysing and Synthesizing Weaving Design Based on the Laws of Prägnanz and Shape Grammar (poster)" (presented at the 5th International Conference On Design Computing And Cognition (DCC), Texas, USA, 2012).

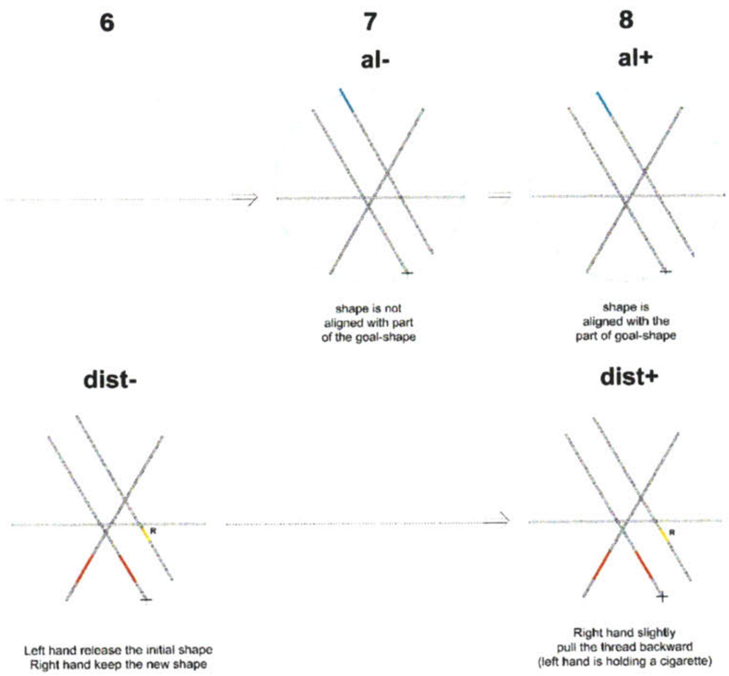

Figure 32. Visual-Haptic Coordination
In the first row, a circle is embedded in the weave as a mental shape representing the lid of the woven basket. From this embedding, a misalignment position between the physical thread and the mental shape is sensed. This visual sensing gives clues to the hands as to which direction the thread needs to move to fix this condition. Here, the long arrow on the bottom row represents the physical intervention to fix the misalignment, where the weaver pulled the thread until both thread and the circle aligned (see the label: **al- → al+**).

In step 9 in Figure 3331, an unequal knotting condition occurred. The area of the new knotting pattern was larger than the area of the existing pattern (i.e., the triangular area between the thread). Here, based on my interview with the weaver about the space between the thread, I presented this condition by adding planes on the empty triangle area between the two threads (i.e., triangular planes)(Figure 3331). These planes contrast the unequal knotting pattern. To fix the asymmetrical knot, the weaver placed his hands on the newly- added thread and then pulled it inward to firm up the knot. As a result, both triangles appeared to be equal.

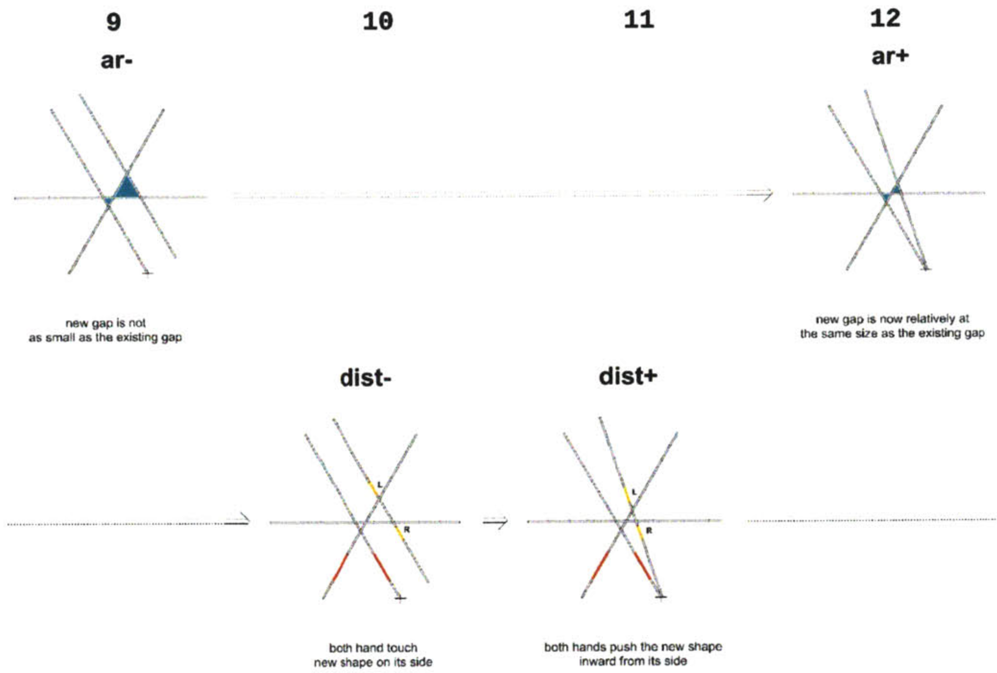

Figure 33. Visual Assessment
The unequal knot in step 9 is represented by highlighting the negative space of the weave (the triangular planes blue). This particular step interprets how the knot condition might be evaluated more in a geometrical way rather than in a structural way using the knotting pattern (see the equating triangle in shape labeled with **`ar-`** and **`ar+`**).

The sensorial computation from steps 1 to 18 interprets embedded mental shapes involved during the weaving process as perceived by the weaver. The shapes are projected visually as mental guidelines that can be *permanent*, as in the case of basket-lid, or *temporal*, as with the triangular pattern of the knotting pattern. In this case, the weaver uses the emerging temporal shapes during the weaving process to help him weave his permanent shape. While embedding emergent shapes in design exploration is usually to inspires new design, recognizing temporary emergent shapes in this weaving activity is aimed more at controlling or shaping the predefined design goal.[113]

[113] In contrast, in random-weaving or sculptural fiber arts, the final shape may not be defined at the beginning, but rather gradually designed upon a series of emergent temporal shapes in an exploratory process, which results in an art piece (source: based on my experience as a student in 3D weaving workshop taught by Nathalie Miebach , MassART.)

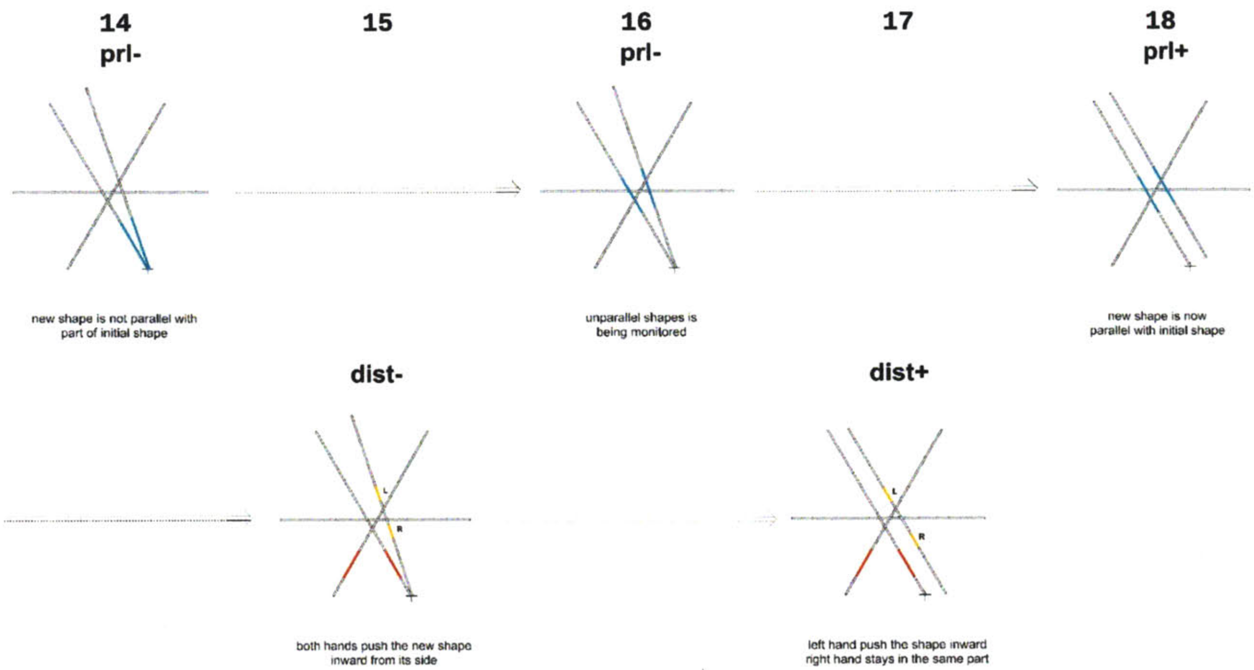

Figure 34. Embedded and Embodied Shape
Notice how the weaver first gazes at the end of the thread to assess the unparalleled condition and embed the 'V' shape, and then shifts his gaze to the knots in the center of the weave and applies physical intervention to straighten the threads. Although he no longer see the end of the thread, the weaver had embodied the 'V' shape in his mind, knowing that parallelizing the middle part of the thread means the end of the threads will also be parallel.

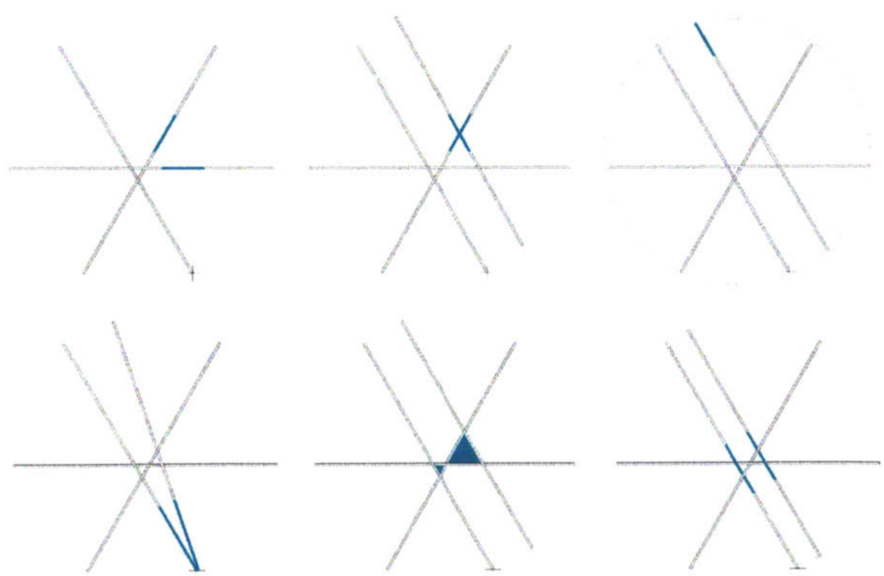

Figure 35. Emergent perceptual shapes
Shapes from my interpretation of the weaver's sensorial experiences show that the weaver may perceive the threads on the weave not as an atomic shape, but rather a continuous shape that could contain many subshapes, either in the physical shape (the thread) or in the space surrounding the threads (e.g., circle and triangle).

Haptic Shape and Haptic Ambiguity

According to Gibson's haptic theory, the weaver senses the shape on the weave using his/her haptic apparatus in three ways.[114] First, the weaver's hand has both a *passive* role, to feel the stress/strain of each knot, and an *active* role, as fabricator of the weaving. Second, the thread, for weavers, is not merely a construction material but also something that performs as the *cutaneous appendages* and *receptive units*, transmitting structural data of the woven object to the weaver's hands as they pull and stretch the thread. Third, the weaver's body performs *dynamic touching* as skin, joint and muscle act together with different degrees of sensitivity. The stretching muscles transmit stress/strain data, the joint's rotation transmits the angle and position coordinates and the skin pressure provides contact information.

To understand the role of these haptic apparatus in more detail, I interpret the weaver's haptic and visual experience from step 7 to step 8 in the following sequences (Figure 34):

In step 0 to 1, the weaver senses the shape in the area where the hand touches the thread. The haptic apparatus involved in this step are mainly in the palm and fingers as the skin makes contact with the thread's surface. Underneath the skin, the weaver senses the thread's stiffness via the muscle's contraction and compression so as to adjust the level of tension of the grip on the thread.

In step 2 to 4, the weaver senses a shape between his visual attentions at the end of the thread and his hand grip as he starts to push the thread to close the gap with the circle (dark-blue shape). In step 5, as his hand and arm muscles adjust the force of the grip and pull the thread (through muscle tension and tactile feedback), his visual attention transmits information about how far the arm should push the thread and how much force should be applied to achieve a desired distance.

[114] See further explanation of Gibson haptic theory in its relation to structural property of weaving in Rizal Muslimin, "Learning from Weaving for Digital Fabrication in Architecture," *Leonardo* 43, no. 4 (July 16, 2010): 340–49, doi:10.1162/LEON_a_00007.

In step 6, the weaver senses a shape from part of the thread between the knots and his grip. Here, in addition to the hand and finger muscles and nerve endings, the arm muscles, tendons, and joints are also involved in sensing the friction of the knotted area. In step 7 and 8, the weaver moves his/her arm back and forth to adjust the force so as to pull or push the thread through with the proper force.

This synchronized haptic and visual coordination guides the shape formation. The visual and haptic apparatus feeds information back to the brain and instructs the arm/hand/finger muscles as to how much force should be applied. In this case, the weaver's muscular force should be larger than the sum of the knot's frictional forces to move the thread. All of this occurs while the visual feedback informs the weaver when this force needs to be released, which is at the exact time as when the shape formed by the thread and the part-shapes of the final design (circle of the lids) are aligned in step 8.

The way the weaver positions his body to correspond to the thread indicates that the haptic-visual coordination might have been mentally calculated, even before the weaver takes action. The weaver grips his dominant hand on the weave not too close to the last knot so as to easily push it, yet not too far from the knot so as to maintain the arm in a stable position and to maneuver the thread.

The weaver's hand position on the thread is in some way analogous to the way an artist holds a pencil close to the tip to draw fine details, and much farther from the tip to make broad strokes in a rough sketch. As the weaver constantly receives feedback from the weave's stiffness through his haptic senses, he can shift the degree of freedom between the arm and the palm. In addition, the left hand lifts the thread to helps reduce the friction between the thread and the floor. The left hand also constrains the thread's degree of freedom to ensure that the thread moves linearly rather than rotationally, to close the gap.

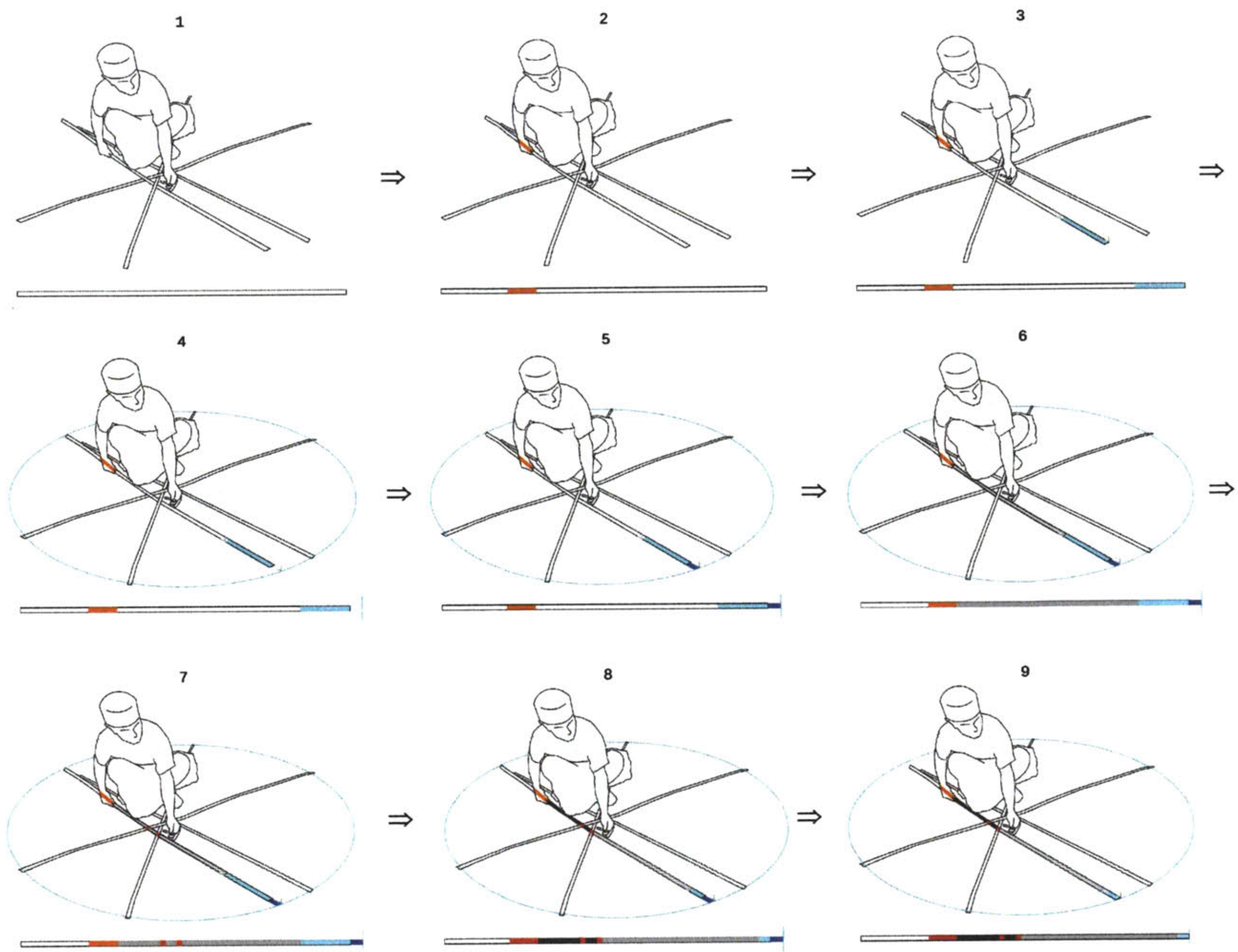

Figure 36. The rise of the haptic shape
The images show a sequence of the weaver's haptic experience in sensing and adjusting the misalignment in the weave (see also Figure 3331). In the first row, after the weaver holds and sees the thread (orange and blue), he projects a circle, as the representation of design goal, and notices the misalignment (dark blue). In the second row, he starts sensing part of the shape that needs to be moved (dark grey area between his grip and the end of the thread). As he starts to push the thread forward, the material responds, as a result of the interwoven knots' friction forces (two red-squares), transmitting the stress information from knot to the weaver's senses. Based on this information, he then focuses on the thread's reaction between his grip and the knots (black), and gradually increases his pressure force to the black area until the thread is placed in the correct position (indicated by the disappearance of the dark-blue area).

Haptic Ambiguity

My interpretation of the weaver's movement and of the angle of his body and limbs helps me to deduce how the weaver senses the shape through his haptic apparatus. In this study, haptic sensing is represented not as a single event but as an assemblage of multimodal sensing experiences, each of which works in collaboration with the others to define the shapes. As there is more than one way to see and embed shapes, [115] the assemblage of haptic actions suggests that there is more than one way to touch or haptically sense shapes, as well. The term *sensing* here is not the same as when a blind person senses or assesses a surface of the ground with a walking stick.[117] In this case, the weaver can see and touch the thread but has yet to decide which part of the thread he should focus on, and how that part will interact with his hand and the other threads. I call this *haptic ambiguity*. In this ambiguity, the shape that he haptically sensed could involve the whole thread, the part gripped by the hand, the part between the knot and the grip, the part between his visual attention at the end of the thread and the knot, or many other possible parts. Different perceived shapes are illustrated in Figure 3735 to show that in searching for an optimal haptic shape for subsequent physical action, the weaver senses the thread as a continuous, not a discrete, shape.

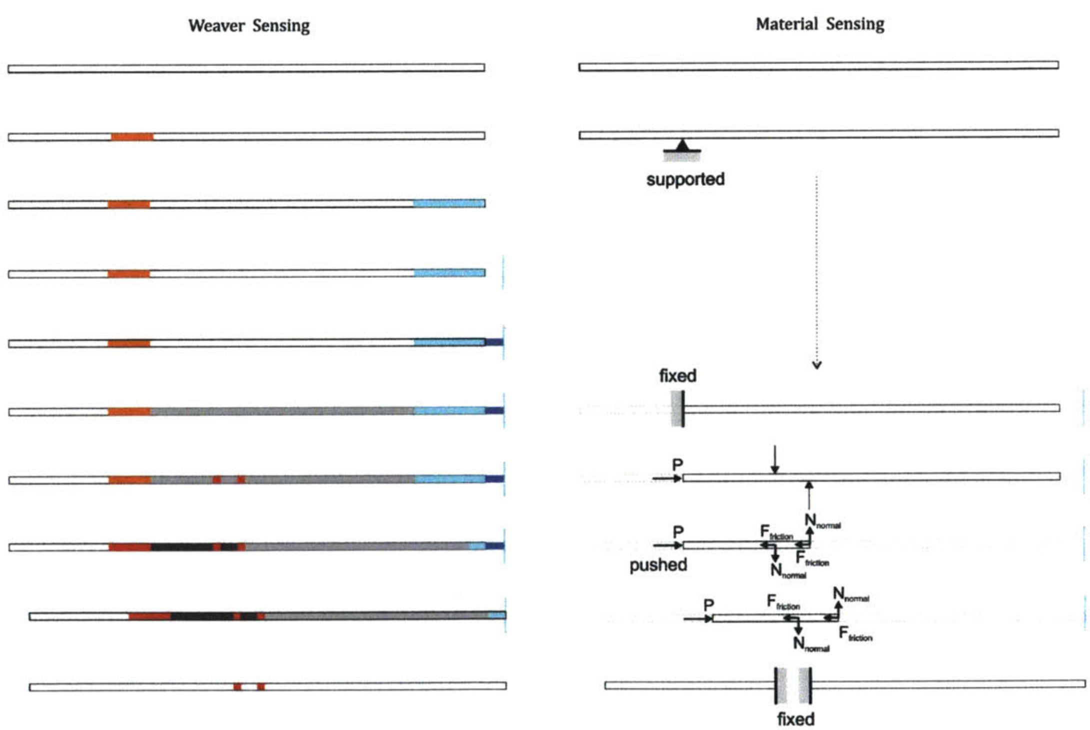

Figure 37. Weaver-Weave Sensorial Exchange
This figure illustrates sensing from the thread point of view on the right-column images as the thread's material properties corresponds to the weaver sensorial experience on the left-column images (see Figure 34). As the weaver senses and perceives the thread differently, the thread also "feels" the weaver in different way (e.g., being supported, being fixed, being pushed, etc.) and responds according to the weaver's reactions.

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[115] Stiny, *Shape*.
[117] Gibson, *The Senses Considered as Perceptual Systems*.

In terms of structure, haptic ambiguity also affects the way the weaver perceives the thread's stiffness. The way the weaver touches the thread changes the thread's stiffness through the reaction applied by the weaver (In structural terms: by applying a fixed support, simple support, pinned support or roller support).[118] In a way, the thread is also 'sensing' the weaver. The thread, in turn, responds by allowing its shape to be altered by the weaver's action, which is vital input for the weaver's sensorial experience. The thread's different structural configurations in the right column of Figure 3735, show that the weaver's touch affects structural sensing of the material. As the weaver applies different types of forces to the thread, (i.e., pulling, pushing, pressing, rolling), he senses the weave as a *perceptual structure*. What is considered rigid in one step could be perceived as flexible in another step, and vice versa.

The contact area of the weaver's haptic apparatus does not always involve just the fingers and palm of the hand. In this observation, the foot also plays a significant role, as the weaver always squats on the threads to firm the weave position. Although his foot seems mainly static, the weaver's body-weight pressure (through the foot) stabilizes the thread positions on one end while his hands manipulate the other end. This position in turn may absorb the stress in the body of the weaver while the hand manipulates the threads. Thus, through the foot, the thread transmits more physical information to the weaver's intermodal perception system.

In addition, the floor surface in this observation also serves as the weaver's external haptic apparatus. This is particularly noticeable during the base-making phase of the basket because the thread tends to bend and curve naturally, thus making it difficult to control. Here, the floor acts as a counterpoint to keep the thread straight and level with the planar surface of the basket-base. The weaver keeps the weave on the floor until the base is finished. When the weaver finishes the base, he stands up and lifts the weave off the floor to start weaving the side of the basket. Now, the weave no longer needs the floor's counterpoint for

[118] Mario Salvadori, *The Art of Construction: Projects and Principles for Beginning Engineers and Architects*, 3rd ed (Chicago: Chicago Review Press, 1990).

support. Instead, the weaver benefits from the thread's bending behavior, which helps him form the vertical side of the basket.

Oriented weaving

The previous section discussed how shapes are perceived through the visual and haptic apparatus during a short period (i.e., in-between steps 3 to 4 in Figure 2726). In the following section, I shift the time frame of my observation to a longer period: the 15-minutes process of weaving the base of the basket (from step 1 to step 13 in Figure 2726). During this longer period, the weaver moves his position several times from one spot to another. His different positions appear to offer different orientations to the weave. In this section, I discuss how the weaver orients his body in relation to the weave, based on the Gibson theory of 'orienting system.'

Gibson proposes an "*orienting system*"to explain how we move, turn, and orient ourselves to a new environments on three levels: (1) permanent orientation to the earth (e.g., to gravity and the support surface such as a grassy hill, concrete street), (2) temporary orientation to events and intriguing objects and (3) locomotion orientation towards a certain goal (e.g., birds flying south, finding our way home while walking in the dark, etc.).[119] In this framework, the weaver's orientation changes back and forth between these levels during the weaving activity. In relation to the ground, the floor helps stabilize the weaver's body while the squat pose serves to stabilize his position. In relation to the object, the weaver's body and eyes are oriented toward the weave in each position (e.g., squatting, standing, moving). In relation to the goal of creating a basket, his squatting position allows him to easily bend the thread to create the desired knots and to create the shape of the basket. (i.e., the weaver squats when he makes the basket's base, and stands when he makes the basket's side-surface.) Thus, his permanent orientation with the surface of the ground, temporary orientation toward the weave and locomotion orientation in making a basket, play significant roles in his position.

[119] Gibson, *The Senses Considered as Perceptual Systems*. p.59

Gibson's orienting system explains how the weaver's body is oriented in space as he weaves. However, this explanation focuses more on how the weaver's body orientation works and less on how the weave is being perceived in different weaver orientations. To analyze how the weaver's and the weave's position are reconfigured in the crafting process, it is necessary to widen the observation parameter to include not only the weaver's body but also the weave itself. In the following, as the weaver moves to different positions (standing, squatting), the direction of his orientation toward the weave is analyzed.

Figure 3836 shows a diagram of the weaver's orientation, as he moves to different positions toward the weave. As seen in the diagram, the weaver's frequent orientation might be constrained by the location of thread-materials stacked near this position. In addition, the camera and my position (which is across from his dominant position) may have caused him, out of politeness, to face me, the observer.

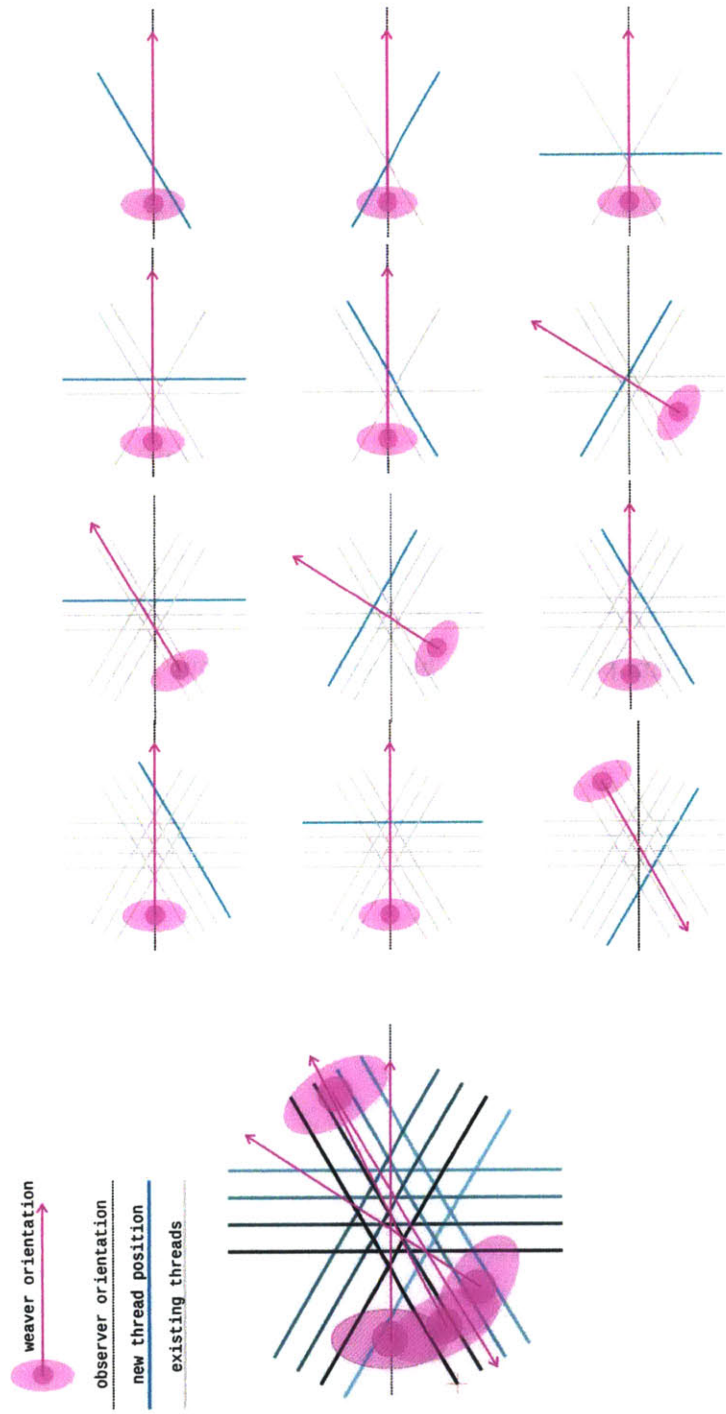

Figure 38. Weaver's motion from the observer's eyes
The weaver's orientation as he moves to multiple positions. The pink ellipse indicates the weaver's position at a point in time and space, and the green line indicates newly added thread in each position. The images are then superimposed (bottom) to shows the weaver's dominant position (the darker thread indicates earlier threads that were added to the weave, e.g., darkest shape is the first thread).

The superimposed images shown in the bottom of Figure 3836 describe how the weaver orients his body toward his work, both functionally to remain close to the stacks of weave material, and socially, so he can continuously face me. However, this illustration does not show how he orients his body in relation to the weave.

For a different perception of the weaver's orientation, I aligned my view with the weaver's views of the weave. In particular, I look at how a new thread is added at each of his different positions. To align our views, I rotated each image in Figure 3836 so that my orientation axis coincides with his orientation axis in a line (see Figure 3937).

I then superimpose these rotated images to identify how the weaver perceives the weave every time he adds a new threading position. The superimposed images in the bottom of Figure 4038 show two dominant thread orientations. The weaver uses these two orientations more frequently, relative to the other positions. The dominant positions indicate that, instead of making random movements, the weaver might be consciously positioning himself with a particular orientation to the weave.

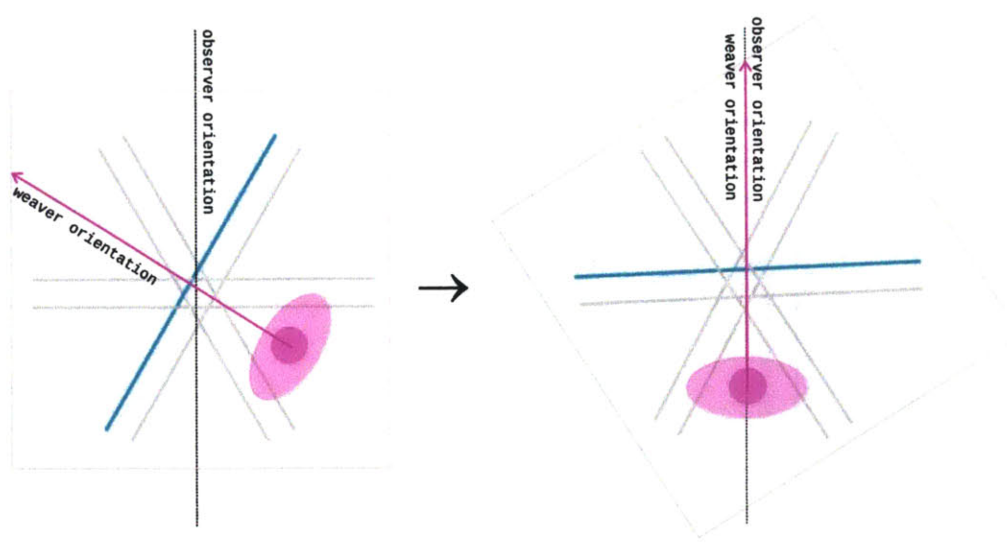

Figure 39. Weaver's – Observer's Orientation Alignment
The weaver's position is justified by rotating the unparallel weaver's orientation (purple-arrow), according to the observer's eyes, into one uniform orientation (vertical axis) perceived by the observer. This way, the observer's view and the weaver's view toward the weave are synchronized in each of the weaver's positions.

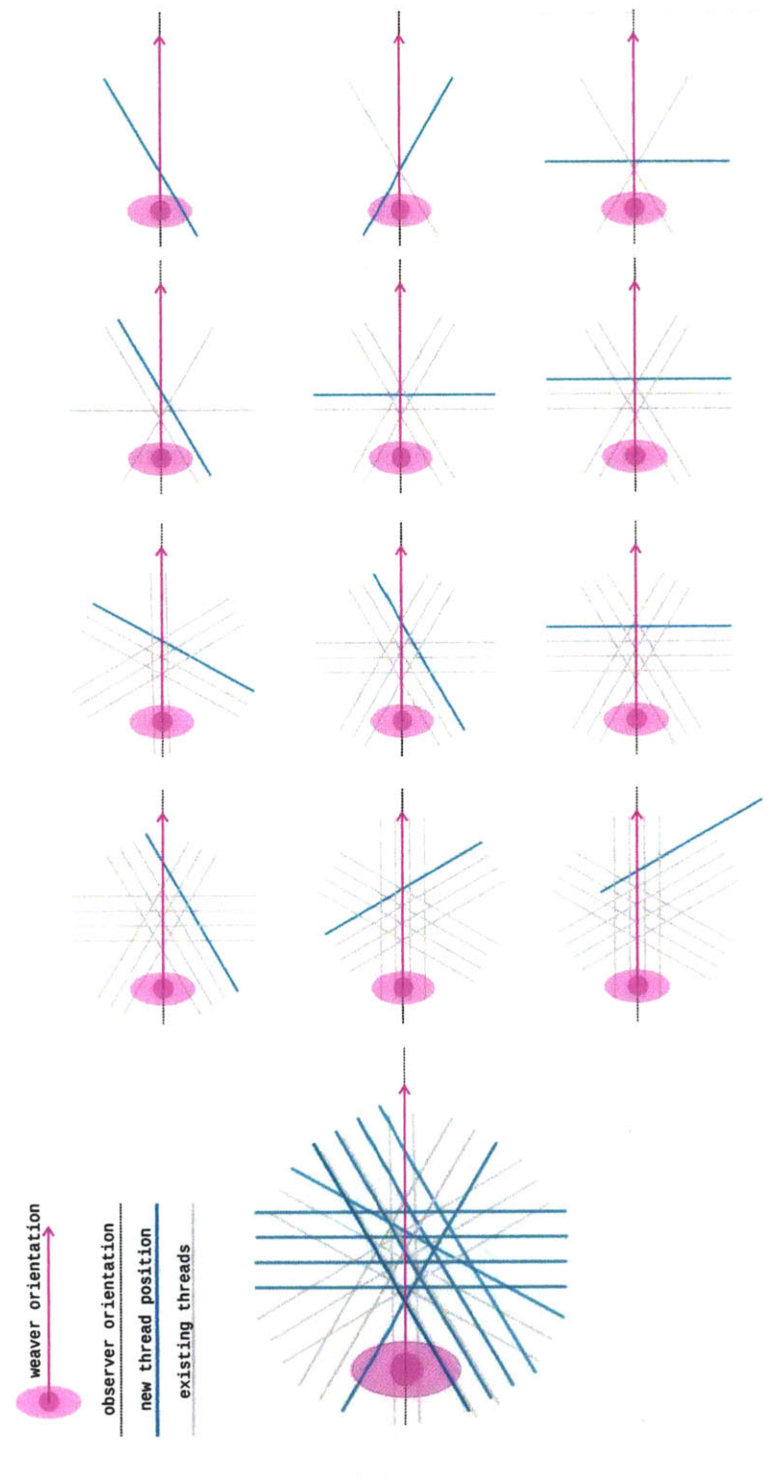

Figure 40. Weave position from the weaver's eyes
The weaver's orientation to the weave from Figure 3836 is justified using the rule in Figure 3937 so that each image would represent how the weaver sees the weave. Each justified image is then superimposed over the others to create one multilayered image (bottom). The green shapes represent the position of the new-added thread in each of the weaver's positions.

Symmetrical Stimulus and Asymmetrical Reaction

Gibson's principle of symmetrical stimulation states that we balance sensory stimulation bilaterally, and we adjust our posture to make the input to the central nervous system symmetrical.[120] Gibson illustrates this by showing how an air-stream influences the body to follow certain odors, how our ears respond to sound by turning the head toward the sound, and how our eyes move to balance the array of light so as to recognize objects. The principle of symmetrical stimulation parallels the dominant thread's position in the weaving process. The first dominant position of the thread_is perpendicular to the axis symmetry of the weaver's body while the second position is tilted toward his right hand (Figure 4139).

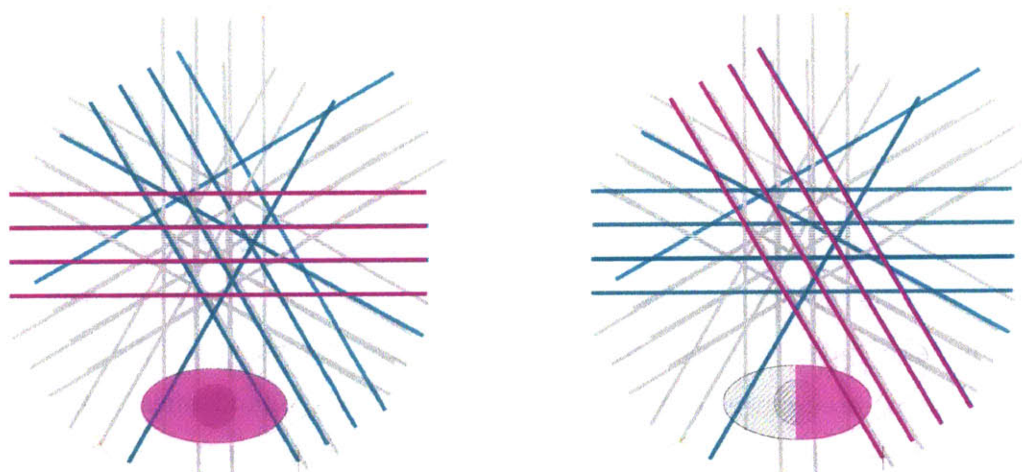

Figure 41. Asymmetrical Making
Two dominant orientations related to the weaver's body's bilateral symmetry (left) and to his right handedness (right) from the superimposed image in figure 40. The orientation of the new threads on the left (horizontal arrow) is perpendicular to the weaver's body, thus allowing his right hand and left hand to manipulate the thread together. The image on the right shows that the weaver always adds the new thread with his right hand, and provides and explanation for the weaver's actions; many new threads are positioned on the right side, instead of on the left or on both the left and right sides.

As seen in Figure 4139, the weaver's orientation seems to correspond to the weave symmetry, the weaver's body's bilateral symmetry, and the asymmetry of the weaver's right-handedness. In the left diagram of Figure 4139, the weaver

[120] Ibid.

positions some new thread perpendicular to his body's bilateral symmetry. This position helps to ensure proper thread position; if a new thread is perpendicular to his body orientation, then the thread is symmetrical with the weave. The right diagram in Figure 4139 shows that the asymmetrical position gives the weaver an optimal distance for his right hand to maneuver the threads (e.g., to pull the new threads inward toward his body).

The motions of the weaver, the thread, and the weave simultaneously complement each other in this view. The bilateral symmetry of the weaver's body and the radial symmetry of the weave allow him to make knots in any position *if* his left and right hands are equally skilled (ambidextrous). For an ambidextrous person, the location of each thread on the weave would be in reach of his two hands, and therefore, the threads would be equally distributed around the weave from one position only.

However, because he is right-handed, the weaver can apply a knot only in a particular gesture according to his right-hand's distance; consequently, he constrains his movements to a particular orientation to the weave. Thus, to apply knots to the rest of the weave, he then needs to move around the weave. The number of different ways to add a new thread, given the weave and the weaver's symmetry, are reduced by the weaver's asymmetric right-handedness in the making process. This asymmetrical-making process may contribute to his 'making style' in weaving.[121]

2.6 Discussion

In this chapter, I have rendered my interpretation of traditional weaving on the site (Kete Kesu, Toraja), from site reconfiguration to bamboo materialization to weaver-weave sensorial experience. This EthnoComputation underlines the role of sensing and calculating in the flux of form and matter.

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[121] This symmetrical reduction of the weaver's body is analogous to the way symmetrical reduction in Shape Grammar helps to define rules for a certain design language.[121] For instance, the order of symmetry of square (eight) indicates eight ways to match the shape in shape-rules, through which many design possibilities could be generated. Design languages using the square can be defined by constraining the square's symmetry.[121]

Sensing and Calculating in EthnoComputation

I begin by portraying the site as a schema, which consists of a set of shapes that have the same level of attention. I call this a non-judgemental view. This portrayal does not diminish the context to become *site-less*. Rather, it shifts the context back into a *pre-site* condition, where meanings of objects on the site are yet to be identified or labeled. Next, I define the site's elements (e.g., weaver, weave, ornament, material) and associate them to form certain relationships (e.g., weaver-weave; weave-material; ornament-weave; weaver-ornament). These relationships provide me with different frameworks to perceive the context in this EthnoComputational study.

Based on these frameworks, I present the role of human interaction in crafting through indirect observation of the bamboo materialization and direct observation of the weaving activity. Both crafts objects and craftsperson's activities serve as my computational interface to analyze the crafting process. With the absence of craftspeople in my indirect observation, I interpreted the rules of how shapes in nature (bamboo trees) are transformed into diverse craft components through the available woven crafts. With the presence of a craftsperson in my direct observation, I studied the ways in which the weaver's activity implies how he perceptually acquires the shapes through his senses.

Hylomorphism Revisited

This process of interpreting a traditional weaving craft was framed on two states: continuous state, by using Ingold's EWO approach in navigating the matter-form, and discrete states of Aristotle's four causal functions: material, formal, efficient and purpose causalities.

The material cause in this study is examined as I perceive bamboo transform from one form to another. In the case of weaving, my perception of the material shifted recursively from a bamboo tree to a bamboo pole to bamboo thread. Because a material-cause can recursively change, in turn, the cause can extend the singular explanation of formal causes of weaving into numerous explanations based on what the material can do (its uses, its flexibility) in different states. For example, a long, rigid bamboo pole can be used to build a linear structure for shelter; long, flexible bamboo threads can help weave a curved surface for a basket; a planar, flattened bamboo pole can be employed to build a two-dimensional partition in a house.

The efficient cause (agent) is represented not merely by the agent's (weaver's) intention but also by how the spontaneous agent's intention emerged from a reciprocal action-reaction in a weaver-and-weave interaction. This action-reaction process is rendered through the weaver's sensorial experience (vision and touch). In supporting the weaver as the main efficient cause, the bamboo material property and the surface of the floor are also considered part of the agency that affects the shape of the weave.

The final cause (purpose) is what use an object or creation offers. The interwoven-craft in this village has various purposes (e.g., to support a sturdy shelter, to carry things, and to decorate.) However, these apparent purposes do not always explain why the weaving technique is chosen by the craftspeople, because other non-woven crafts serve similar purposes and even have similar forms. For instance, in Toraja's traditional architecture (the Tongkonan), both wooden Tongkonan and interwoven-bamboo Tongkonan share similar forms; thus weaving is not unique to the Tongkonan's form. However, in the other causes, such as material and efficient causes, one can observe certain features, such as the economic aspect of the construction process, that are unique to weaving. Building a Tongkonan with bamboo can save construction cost and time because of the abundance of low-cost materials (bamboo surrounds the village) and the high supply of a labor-force (weaving can be performed by many people). Material and labor affordability could suggest other final purposes, such as funding issues in cultural sustainability to ensure that the cost of building temporary Tongkonan to accommodate guests during ritual ceremonies remains affordable.

Thus, by investigating the other causes — material, formal and efficient — we can identify final causes, which in this case may not necessarily be drawn from the artifact as a final product (e.g., a house is used to shelter people, a basket is used to help a person carry things), but rather in the process between matter and form.

Ethno-Computation as Cultural Mimesis

The study employs a computational framework based on my personal experience in interpreting traditional weaving. My interpretation, however, does not intend to identify and verify the original rules of traditional weaving in order to establish 'a science of weaving.' It is meant, instead, to reconceptualize ways with which to appreciate the craft of weaving. In this new appreciation, we can then reestablish and enrich our knowledge to develop weaving, and use this new knowledge to further interpret and reinvent similar artifacts. Through such reconceptualization and enrichment, we can learn multiple ways to apply weaving techniques, even beyond the traditional context (e.g. modern architecture, engineering, etc.).

Ethnos encompasses more than ethnic groups; it encompasses humans, individually or collectively. In EthnoComputation, culture is defined as the way humans represent how they understand their environment and craft is one of the manifestations of such culture. This case study of traditional crafts-making should not be viewed as an attempt to place a rigid boundary between traditional crafts and modern technology, but rather as a means to enable people from different spheres to exchange methods by which to compute shapes in crafting. Just as this study represents the way the Toraja people manifest their understanding of the environment through crafts, so EthnoComputation might be used to calculate the interaction between humans and crafts in an advanced engineering context. For instance, EthnoComputation can help to understand how engineers study and represent the renowned nature-properties in biomimetic technology, or how fabricators arrange their rapid-prototyping tools in digital manufacturing. Recalling Herbert Simon's example, instead of seeing the bird as an object, an EthnoComputation study would focus on the interaction between the aerospace engineer and the bird as a research subject, in particular analyzing the way in which the engineer perceives the object in nature and translates it into an artificial object. Interpretive rules and schema from these examples could serve as design currency in exchanging design logic and improving design affordances across cultures and disciplines.

3 COMPUTATIONAL WEAVING

3.1 Outline

This chapter aims to provide computational design methods to reinvent traditional weaving in architectural design.

The ubiquity of weaving across scales in Toraja implies the presence of an intelligible method shared among craftspeople, which allows them to use a similar method in various applications. For instance, the method used to weave a basket is similar to the method used to weave a wall-partition, floor mat, and accessories. In this application, weaving principles embody different material properties, e.g., more rigid for shelters, and more flexible for wearable items. Through the tacit environment, the weaving method's comprehension and the weaving design intention are mediated during the making process.

In this chapter, I provide computational design methods with the intent of aiding designers to reinvent architectural weaving in an explicit manner; this is comparable to my interpretation of the way the traditional knowledge assists Toraja craftspeople in advancing weaving crafts in a tacit manner.

The chapter is divided in two sections:

In the first section, I describe the process of a basic Weaving Grammar development. The Basic Weaving Grammar provides methods to reinvent weaving design by reformulating the way thread is composed on the weave, using a set of rules. The grammar development focuses on the moment in which the weaver adds a new thread to develop a particular weaving geometry. From this focus, I further discuss how the grammar evolves, from the weavers' mental shapes and the weave's physical shape, to a set of rules using Euclidian transformations and principles of symmetry. Several examples demonstrate the way rules in the Weaving Grammar generate weaving design computationally. Using the generative rules, traditional weaving designs as well as other designs can be computationally analyzed and synthesized.

Following the description of Basic Weaving Grammar development, I present four case studies in which I examined the grammar's contextualization for architectural application. To evaluate how a builder learns how the weaving grammar works, I conducted a weaving grammar workshop, where I taught the grammar to people from different craft disciplines in Toraja, and to children from different age groups in Cambridge. To investigate whether the architectural weaving designs generated from the grammar are buildable, I inspected the design's structural integrity with a Finite Element Analysis and Compressive Test. With the rule readily understandable and the design structurally acceptable, I further tested the design's constructability by building a mock-up installation in Toraja. In the construction process, I inspected how the rules assisted the construction process. The two workshops, in Cambridge and Toraja, showed that individuals can readily learn shape rules, either visually, with paper and pen, or physically, with wooden modeling pieces. The installation inspection on the site showed that the rules helped the builder to assemble a design efficiently with a minimal learning curve.

In the second section of this chapter, I explain the method of reinventing weaving design using an abstract weaving grammar by perceiving weaving material properties in different ways. This method was inspired by the way the traditional weaver engaged with his materials (described in the previous chapter). Different ways of perceiving materials allow traditional weavers to apply weaving principles to different forms, such as partitions, roof structures, baskets, mats, hats, etc. Thus, the aim of formulating material perception into an abstract weaving grammar in this section is to accommodate different physical requirements in architectural weaving, in particular, the requirement pertaining to material properties (e.g. lightweight, flexible, rigid). Learning from playful material application in traditional weaving, architectural weaving is hoped to be adaptive to different types of material.

Towards this goal of adaptability, I incorporate Finite Element Method (FEM) approaches to the idealization of a shape, and its mechanical properties, into discrete model. In this section, FEM idealization principles are represented with shape grammar notation. With this notation, I develop a grammar to reinvent weaving, benefiting from both shape grammar's visual calculation and FEM's mechanical representation. The combined visual and mechanical representation in the grammar allows a weaving design to respond to the external forces on the weave based on its material composition and geometrical configuration. Several examples of the grammar computation in this section reveal the relationship between weaving and the other crafts, such as tensegrity and folding, in a generative and explicit manner.

In the last section of this chapter, I reflect on the role of computational design in reinventing architectural weaving.

3.2 Basic Weaving Grammar: On the Language of Weaving Design

Introduction

This section illustrates the process of developing a basic weaving grammar based on the moment at which the weaver adds a thread to the weave in developing a particular geometry. The aim of this grammar is to provide a comprehensive architectural weaving design methodology, from formulating design intention, defining weaving action and evaluating weaving condition.

Shape Grammar computation methods need certain basic requirements, i.e. initial condition, shape rules and shape computation (see page 22 and page 44). To develop a comprehensive weaving grammar, the cascading processes from weaving intention to weaving action to weaving evaluation in the grammar have to be well integrated. To serves as an initial condition, the weaving intention needs to be visually defined. To initiate a computation, the left-hand shape of the rule needs to match the initial condition. To compute the shape recursively, the right-hand shape needs to match the left-hand shape within the grammar. Furthermore, to evaluate whether the generated shapes are woven, the grammar should be able to evaluate the weaving condition and follow up the condition properly.

In the following, the development of rules for Weaving Grammar is rendered in three phases:

Phase 1: Defining Weaving Intention
Phase 2: Developing Weaving Action
Phase 3: Evaluating Weaving Condition

Following the development of the grammar, case studies of the Weaving Grammar application in traditional context are discussed.

Phase 1: Defining Weaving Intention

Phase one provides a computational method to generate certain geometry for the weaving grammar as the design intention -- specifically, in developing the left-hand shape for the rules in Weaving Grammar.

The computational method discussed here is inspired by the mental and physical shapes from the sensorial computation in the previous chapter. The EthnoComputation study shows that the weaver utilizes mental shapes to make sure the threads are woven into his design intention, a triaxial woven basket. One of the mental shapes interpreted for this intention is the negative space between the threads – the polygon. Considering the key role of the polygon in weaving geometry, this phase begins the computational process by parameterizing the polygon (Figure 4240).

The polygon in this grammar is construed as an assemblage of isosceles triangles that are rotated using the polygon's center point. The rotation angle (α) equals 360° divided by the number of polygon sides (n).

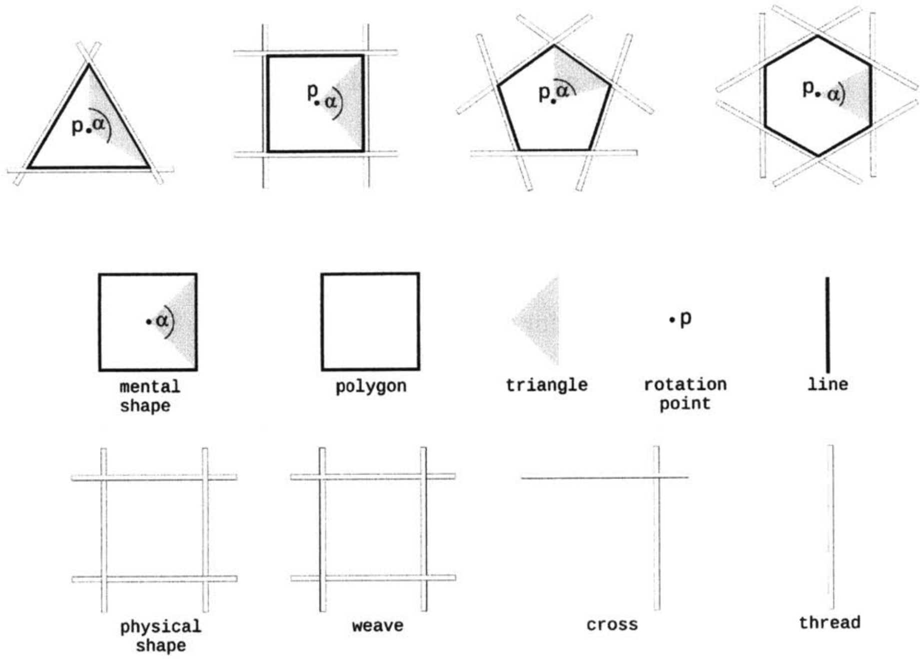


Figure 42. physical shape and mental shape
Mental shape is represented as an n-sided polygon. The parametric description of the polygon can define different types of weave (e.g. bi-axial and pentagonal weaves).

The rotation of the triangles in constructing the polygon is parallel to the rotation of the threads in weaving the weave. As the polygon's side coincides with the threads, the number of the threads equals the number of polygon sides. As the triangle baseline coincides with the *part of the* thread that defines the polygon, the triangle effectively focuses the user's visual attention on that particular part of the thread. In addition to the triangle, the role of the point also corresponds to the thread's addition. The point serves not only as an axis for the rotation, but also as a visual reference in evaluating the polygon's symmetry as the weave develops. With this mental-physical shape association, the shape relationship between the thread and the triangles can now be represented. In the following, I use a square as a polygon to demonstrate how a set of rules adds the triangles and the rotation point to transform the thread parametrically (Figure 4341).

Rule R1 establishes the coexistence between the mental shape on the thread (line) and off the thread (triangle), by adding the triangle to coincide with the line (the line's length represents the thread's length). This rule is defined by parametric descriptions pertaining to the polygon: (a) number of a polygon sides

(n) and the triangle's angle: $\alpha = 360° / n$.[122] If the number of polygon sides changes, for instance, from pentagon to hexagon, the shape of the triangle will change accordingly.

Rule R2 adds a rotation point **P** within the triangle as a reference to weave the thread into a polygon with rotational transformation. The role of the triangle in this rule is to provide boundaries for placing the rotation point. Placing the rotation point anywhere within the triangle, and within $\alpha \leq 360° / n$, will guarantee the rotated threads intersect with the others. Otherwise, if the point is placed outside of the triangle or $\alpha > 360° / n$, the rotated threads will not coincide with or intersect one another; such threads cannot be woven. The point location's parameter (x,y) in this rule provides options to generate the thread into various weaving styles based on different rotation axis (a discussion on how the point location affects the weaving design is provided in page 103 to page 108).

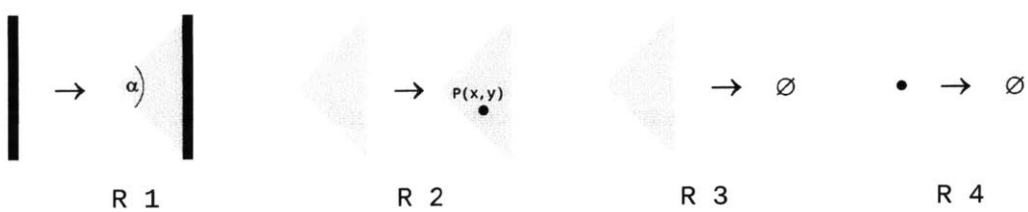


Figure 43. Rules to define the left-hand shape Weaving Intention
Given a predefined n-polygon, a thread as a line and the mental shape as a Weight is defined as the basis of the weaving geometry. R1 adds the mental shape as part of the rule. R2 adds the rotation point P to generate the weave within the triangle. R3 and R4 'erase' the mental shape.

Rule R3 erases the triangle to signify that the process of defining the basic geometry is finished. In other words, the question of 'what type of polygon should I weave' is answered. The absence of the triangle fixes the point location because the point can only be changed with the triangle present (as notated in rule R2).

Rule R4 deletes a point for two reasons: First, the deletion of the point returns the line into its initial condition. Thus, makes the line is ready for yet another new intention development. Second, without a point, the line can match

[122] The mental shape can be any type of triangle (beside isosceles) to define various mental shape. There could be more than one rule defining the shape. However for clarity reason, here, I focus only on the isosceles triangle and basic polygon.

any lines in the computation. Thus, it makes the weaving intention becomes less deterministic.

The development of the weaving intention in this phase is summarized in Figure 42 through the following sequences: [1] given a design intention (polygon), R1 defines the parameter for the weave's geometry (triangle). [2] Given the weave's basic geometry, R2 defines the weaving style (point). [3] After the basic geometry and the style have been defined, R3 fixes the weaving intention for the next phase. Shape in step 4 and step 5 serves as the left-hand shape for the weaving action in the next phase. The process of generating this shape is compiled into rule R1-3 and R1-4.

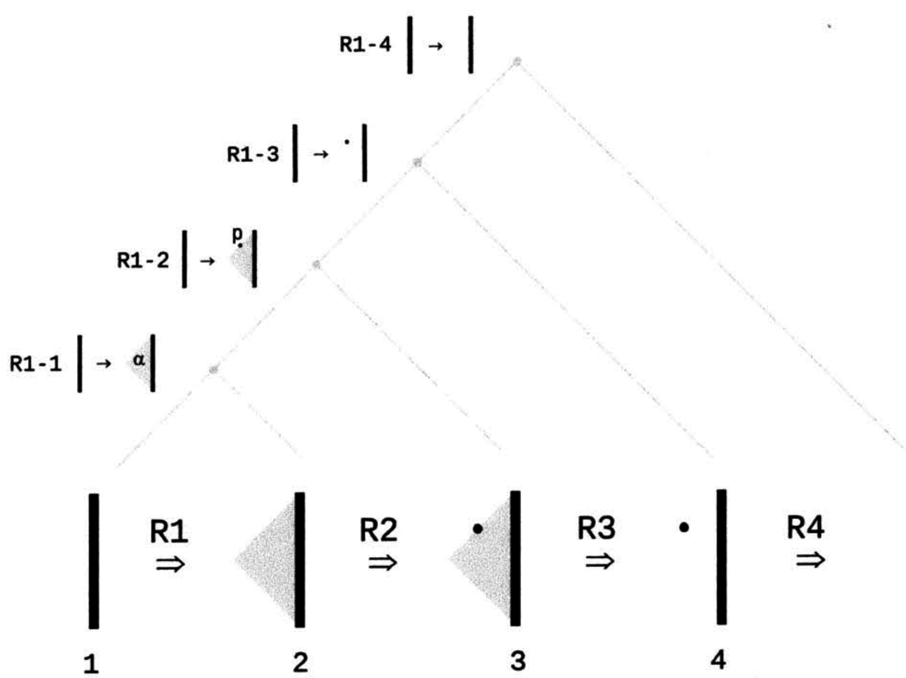


Figure 44. the development of weaving Intention
Given a thread in the first step, the second and the third steps answer the question of 'what polygon should I use' and 'how will the weaving be styled'. The fixed point in the fourth step sets up the condition for the weaving action.

Phase 2: Developing Weaving Action

Phase two provide procedures to define rules for weaving action. In this phase, weaving action refers to the addition of a new thread over the existing thread. Rules to add the new threads, as the right-hand shape, over the initial thread, as the left-hand shape, are discussed in the following:

Rule R 55 is parametric and corresponds with the design intention from phase one. This rule adds a new thread over the initial thread with rotational transformation (Figure 4543). The rotation point is point ***P*** from rule R2, and the rotation angle is alpha (α) from rule R1, i.e., $\alpha = 360° / n$. to modify the angle between the initial thread and the new thread. Applying different values of α would create different types of polygon, hence different weaving geometries (e.g. hexagon, pentagon, octagon, etc.).

R 5 <α=360°/n>

Figure 45. Additive Rule to define the right-hand shape for weaving Action

Because the right-hand shape matches the left-hand shape, rule R5 is generative -- i.e., it can be repeated several times. With one point, rule R5 generates threads in cyclic weaving composition. To develop different weaving compositions, such as linear or cluster composition, a rule to create new rotation points is required, to propagate the weave in different directions.

Rule R6 transforms a new rotation point into different locations based on the line's symmetrical properties (Figure 46). A line in 2D space has a symmetry order of four, i.e. [1] by a 360° rotation [2] by 180° rotation [3] by reflecting on the thread's lateral-axis and [4] by reflecting on the thread's longitudinal-axis. The symmetry order of four indicates that new rotation points can be placed into four locations. The parametric description in figure 46 encodes description for the symmetrical transformation. S = symmetry number and [t(x)] = a set of number of transformation based on the order of symmetry.

R 6 <s,[t(x)]> R 6A <s,t(x)$_1$> R 6B <s,t(x)$_2$> R 6C <s,t(x)$_3$>

Figure 46. Shape's order of symmetry as the basis of transformation
R 6 generates the transformation axis based on the four orders of symmetry of the shape. This axis then helps generate four locations for the new rotation points (blue points). Variables indicates the symmetry number. Variable t(x)n indicates the transformation used to generate the point based on the shape's symmetry.

Lattice in figure 47 shows the computation of R4, R5 and R6 in adding and erasing the point in the thread relationship. The rotation point position in the thread relationship is critical in defining weaving action. In the first three steps, after rule R5 adds a new line, rule R6 adds a new rotation point for the new line. In the last three steps, Rule R4 erases the initial point, and again erases the new point. Accordingly, the line relationship in step 6 has no points. Thus, R6 improves the generative aspect of rule R5 by adding a new rotation point, while R4 fixes the thread relationship in rule R5 operation by erasing the point. The weaving style can be varied, but remains in the same basic geometry (e.g. hexagon or pentagon).

The resulting shapes in the bottom of figure 47 express possible right-hand shapes to generate weaving design for a certain basic geometry. Based on these shapes, rules for weaving action are defined by pairing the thread from phase one, as a left-hand shape, and thread relationships from figure 6 as the right-hand shape (The rule computation is discussed later in page 106).

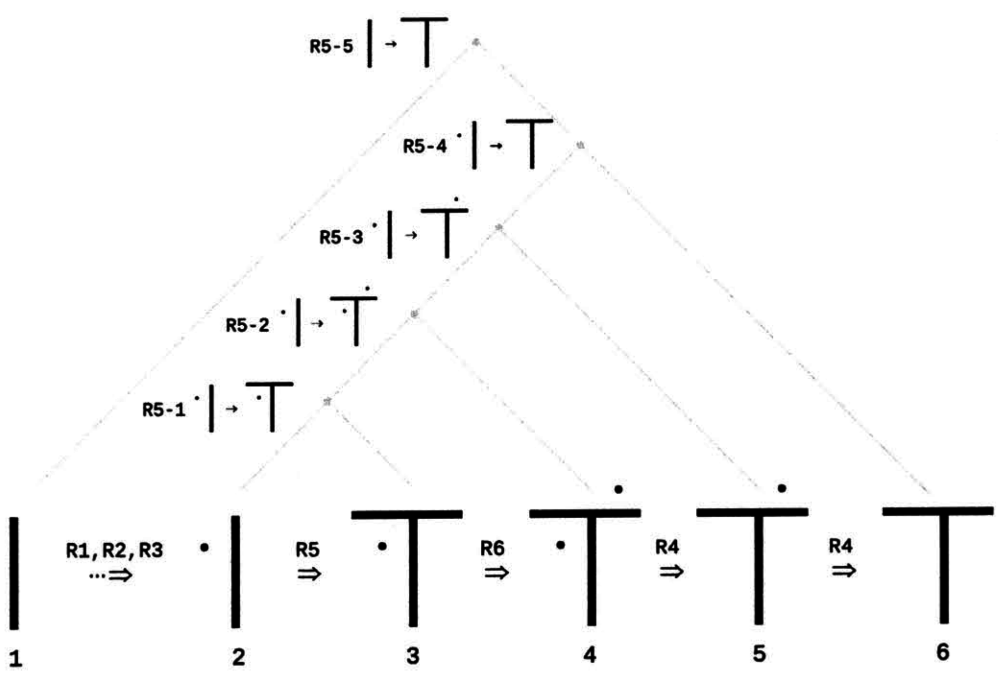


Figure 47. A new rotation point for the new shape
Based on the left-hand shape from phase one (in step 1 and 2), a series of shapes is generated with additive rule R5, transformation rule R6 and erasing rule R4 (step 3 through 6). The new shapes serve as right-hand shapes. By pairing the left-hand shape in step 1 and 2 with right-hand shapes from step 3 through 6, series of additive rules to add new thread are developed in the lattice. Rule R5-1 through R5-5 defines the weaving action for the grammar, where R5-1 to R5-4 is deterministic and rule R5-5 is a non-deterministic.

Phase 3: Evaluating Weaving Condition

Phase three describes procedures to evaluate whether the designs generated from the grammar are interwoven or not. It based on the way the weaver evaluates the cross on the weave (see step 4 and 5 in figure 30). In particular, the interwoven condition is evaluated through the over-and-under knot conditions on the weave. Rules to evaluate the knot condition and rules to fix a knot in a non-woven condition are provided in the following steps (see figure 48):

The first step provides a direction to evaluate the knot when the weave is being developed or when the weave is finished. In developing a weave, rule R8E visualizes an arrow onto an initial thread. In a developed weave, rule R8A visualizes arrows on all threads to guide the knot evaluation within the weave in order.

The second step evaluates each knot condition in the weave. By following the direction of the arrows on the thread, one can trace and evaluate the over-and-under condition of the weave in order. As the evaluation progresses, Rule R8B to rule R8G assigns values for a counting variable *k* to each knot.[124] [125] If the arrowed thread is over another thread, then k is added by one: $k \rightarrow k+1$ (as in rule R8F and R8B). If another arrowed thread is under the other thread, then k value does not change, $k \rightarrow k$, but the arrow direction is reversed (rule 8C).

The third step validates whether the weave is interwoven or non-woven based on the counting from R8B-R8G. If the total k equals the number of polygon sides ($\sum k=n$), then the design is considered interwoven. If the total k is less than the number of polygon sides (($\sum k<n$), then the design is non-woven.

If a non-woven condition exists, R8D-a and R8D-b could fix this condition by switching the reversed-arrowed thread position to the over or under the other thread. The thread's new position changes the k value, such that $k \rightarrow k+1$.

[124] Knot counting in this evaluation is derived from Alexander-Conway polynomial, see J. W. Alexander, "Topological Invariants of Knots and Links," *Transactions of the American Mathematical Society* 30, no. 2 (1928): 275–306, doi:10.1090/S0002-9947-1928-1501429-1. and Sossinsky, *Knots.*
[125] Mathematical Society American, *Applications of Knot Theory: American Mathematical Society, Short Course, January 4-5, 2008, San Diego, California* (Providence, R.I: American Mathematical Society, 2009).

Applying R8D recursively on the other reversed-arrow would increase the k value and eventually equalize k and n. This equalization turns the non-woven condition into an interwoven condition. However, R8D does not need to be applied to all knots. Some arrowed threads may be kept under the other thread deliberately, to create a weaving pattern.

The fourth step proposes what to do in a woven condition. The interwoven condition signifies that the computation to develop the weave should stop running. Otherwise, it will keep generating more shapes to overlap the existing shapes. The computation of rule R5, for instance, will continue running as long as there is a point inside the polygon. Unless the overlapping weave is part of the design goal, previous rules need to be recalled to stop the computation, either by erasing the point with R4, $\sum k=n$: R4, or by moving the point into a different position with R6, $\sum k=n$: R6. The former stops the weaving action. The latter generates new weaves in different directions (see the last iteration in figure 48).

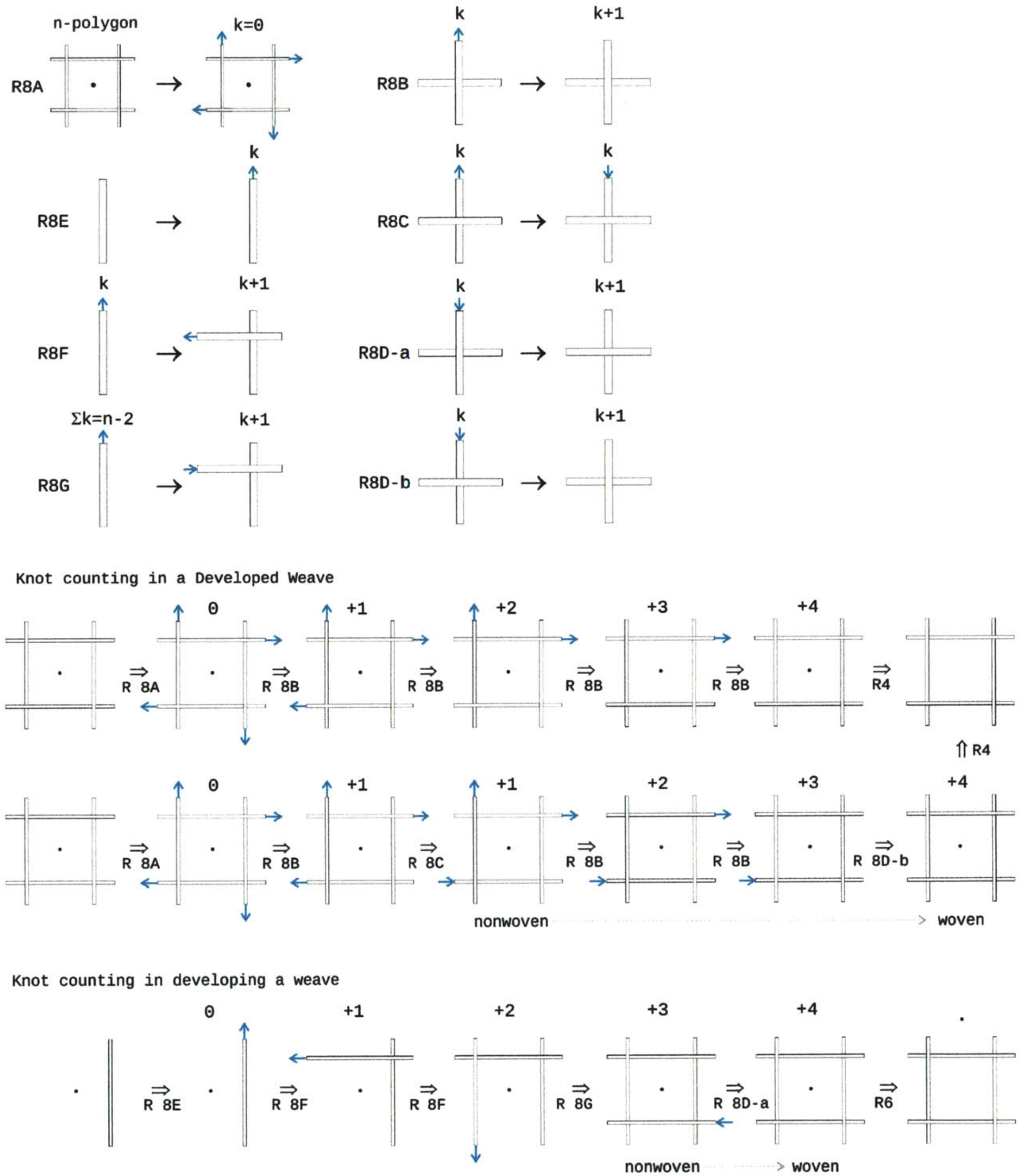


Figure 48. Knot Counting
The series of rules at the top evaluates whether a weave is woven or not. Three iterations show how the rules work in different contexts, i.e. in evaluating the developed weave (middle), and in evaluating the weave as it developing (bottom). Example iterations in the developed weave are provided with two cases: a case when the weave is woven and a case where there is a cross that makes the weave non-woven. At the end of the iterations, two rules follow up the woven condition differently. R4 stops the computation by erasing the point, R6 continues the computation into the other direction by moving the point.

Discussion

This section discusses the computation process of the set of rules defined in previous phases. In particular, the discussion highlights the pivotal role of the rotation point in determining and liberating the computational weaving process. First, I discuss how the point position affects the weaving style. Second, I illustrate how the point's presence or absence play key roles in the iteration process of the grammar.[128]

Point's Determination

The point's position directly affects the shape's relationship in the grammar and therefore, may lead to a variety of styles in the language of weaving grammar.

To understand how the rotation point determines weaving styles, the point location in rule R2 is constrained based on the underlying characteristic of the shape's geometry. Three parametric rules in figure 49 represent the rotation point interpolation within the triangle. R-2A places the rotation point along the triangle reflection axis, R-2B places the rotation point along the hypotenuse lines, and R-2C places the point in any location inside the triangle.

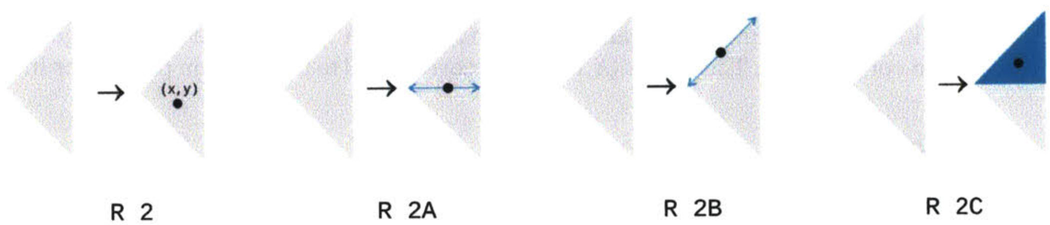


Figure 49. Rotation Point Interpolation
The rule-based design represents four 1D space options (blue lines) for the rotation point interpolation within the triangle to understand the effect of each option in the rule iteration process.

Different point interpolations in the set of rule R2 are used to define three action rules in a set of rule R5: rule R5A, R5B, and R5C (Figure 5048). To illustrate the point's location effect in weaving style, each of these rules is computed to

[128] The point, also known as a label, in Shape Grammar provides direction in rule iteration. For more example G. Stiny, "Ice-Ray: A Note on the Generation of Chinese Lattice Designs," *Environment and Planning B: Planning and Design* 4, no. 1 (1977): 89–98, doi:10.1068/b040089. And T W Knight, "Transformations of the Meander Motif on Greek Geometric Pottery," Design Computing, no. 1 (1986): 29–67.

generate new shapes. As shown in the iteration in figure 50, different designs generated by rule R5s illustrate how the rotation point from rule R2s determines the weaving style. R-5A produces a shape that resembles a Biaxial-weaving pattern (plain weave). R-5B and R-5C produce a shape similar to a Reciprocal Frame, where R-5C results in an extended intersection at the end of the thread. (I detail this Reciprocal Frame later in this chapter.)

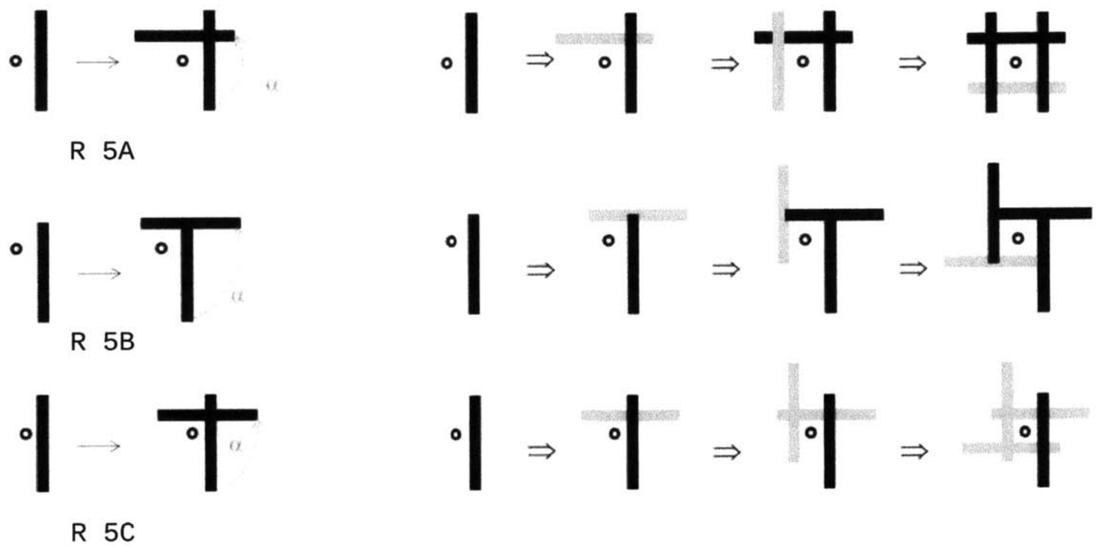


Figure 50. Point's Determination
The different rotation point locations in each rule (R -5A to R-5C) determine the generated design composition. The letters (A,B, and C) correspond to the rotation parameter in R2.

Point's Liberation

The computation in Figure 5048 shows many possibilities for generating weaving designs. However, the resulting design will always be in a cyclical composition because it has only one rotation point that matches the initial shape and allows the rule to run the computation. To expand the computation, rule R6 allows the addition of a new point for such shapes.

Previously in Figure 4644, R 6 shows the thread represented as a line in 2D space that has an order of symmetry of four. By using the shape symmetry as the transformation basis, the rotations point is copied to its new location: [1] by 180° rotation-R 6A, [2] by reflecting on the longitudinal-axis – R 6B, and [3] by reflecting on the lateral-axis – R 6C.

To see how different point impact the weaving design process, the set of rule R6 is used to add a new point for shape relationship in rule 5B. Rules 7A, 7B and 7C correspond to rule 5B in terms of shape-relationship, as well as to the set of rule R6s in terms of new additional points. With the new point, the generative performance of rule 5B is improved. The new set of rule R7 is able to generate design in new directions, away from its original location (Figure 5149).

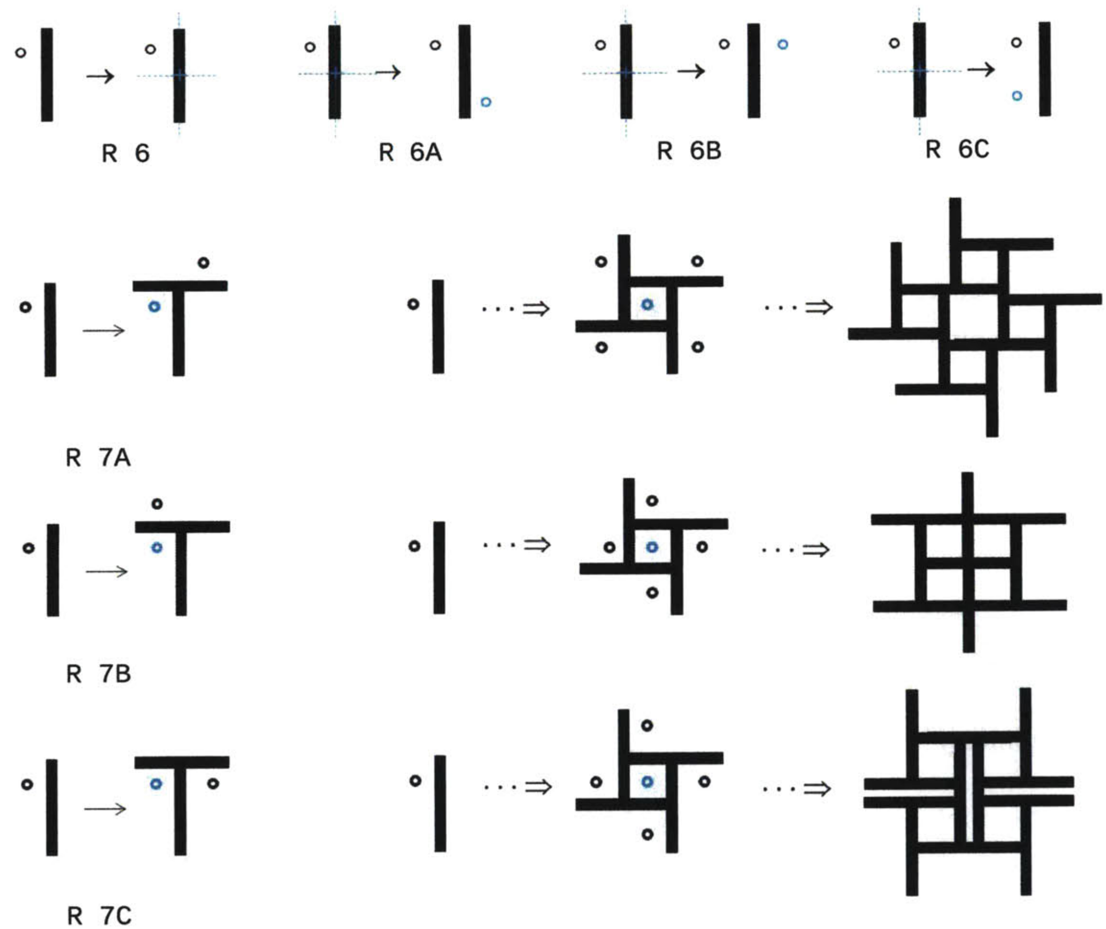


Figure 51. Liberation of the Point
Four different weaving styles are generated from the same shape relationship in R 5A, yet varied with different rotation point locations by R 6's.

The transformation of rule R6s seems to echo in rule R7's iteration. Figure 5149 reflects the characteristics of a certain symmetrical composition from R 6's. When rule R 6A calls for a 180° rotation, the new design generated using R 7A also has a 180° rotational-symmetry composition. When R 6B uses the thread's longitudinal axis to reflect the point, the new design using R 7B also generates a reflective-symmetry composition based on the same longitudinal axis. Similarly, when R 6C calls for a lateral axis, the R 7C computation also generates a reflective-symmetry design on the lateral axis. Thus, when a designer uses different transformation in R 6, (s)he can anticipate these symmetrical characteristics in the final designs.[129]

Nevertheless, regardless of the different symmetrical transformations, all designs in Figure 5149 express some consistency in terms of design language, as they are generated by the same shape-relationship as in R 5B.

On picking and adding the thread

The weaving intention, weaving action, and weaving evaluation have been defined into a set of rules in this grammar. Within this series of rules, the decision process, as it relates to how a particular shape and rules are chosen and computed, needs to be based on certain understandings of the characteristics of the rules.

In the following, I discuss some considerations for a particular moment when a thread is about to be picked and added onto the weave, considerations such as 'Which part of the thread should I begin with?' and 'Where to add a new thread? In discussing these considerations, I illustrate the way the left-hand shape and/or right-hand shape of the rule characterize/s the weaving action in this moment.

On which part of the thread should I begin?

The rule begins by matching the initial condition with the left-hand shape of the rule. Thus, the left-hand shape determines which part of thread to begin with. In this grammar, the left-hand shape is divided into two types: a line with a point and without a point.

A line with a point specifies a particular part of the thread to be computed. The ratio between the line length (l) and the point's distance to the mid-point of the line (h) constrains the matching process (Figure 5250). As a mental shape,

[129] For more example on how shape's symmetry determine the rule iteration, see T. W. Knight, "Constructive Symmetry," *Environment and Planning B: Planning and Design* 22, no. 4 (1995): 419–50, doi:10.1068/b220419.

points and lines can be embedded onto the thread in different ways. However, the embedding must follow the ratio. Different embedding may vary the size of the polygon, e.g., the shorter the point's distance to the thread, the smaller the polygon, and vice versa. Yet, within this size variation, the line-point ratio ensures that the style is consistent.

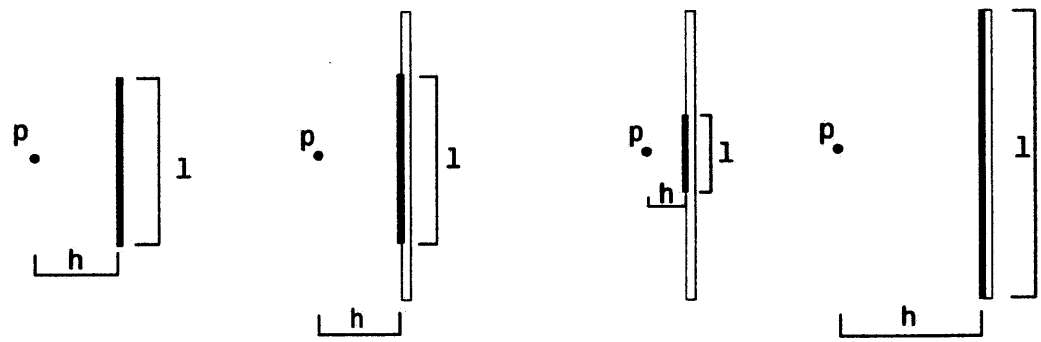


Figure 52. Ratio in point and line relationship in embedding shape on the thread

A line without point suggests that any part of the thread can be computed. Without a point, there is no ratio to follow. The rules in Figure 5351 show a left-hand shape without the rotation point as an initial shape. Any matching line found during the computation process, whether it is a whole thread or part of a thread, can run this rule. As a result, as shown in figure 12, the weave may have one particular style, or another.[130]

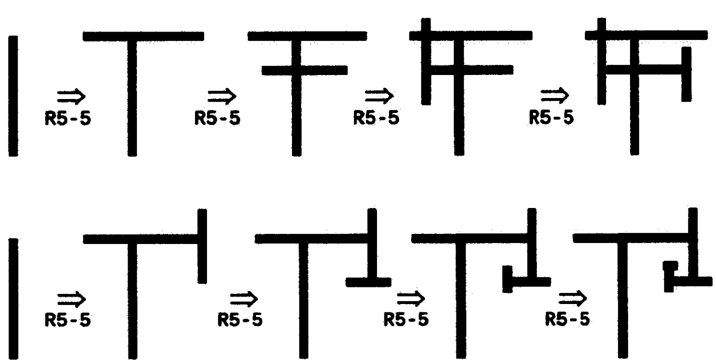


Figure 53. What shape to compute?
By embedding the initial shape in a different way, the generated designs could be free of a stylistic constraints.

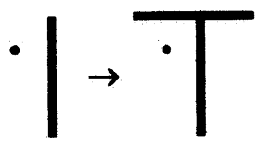
[130] For more examples on how a shape rule and a shape relationship are generated under non-deterministic approach to create different designs, see T. Weissman Knight, "Languages of Designs: From Known to New," *Environment and Planning B: Planning and Design* 8, no. 2 (1981): 213–38, doi:10.1068/b080213.

Where to add a new thread?

After the left-hand shape finds its matches, a rule will substitute the matched shape in the iteration with the right-hand shape of the rule. This substitution indicates where the new shape should be located.

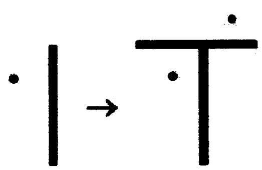
This Weaving Grammar contains rules where some of its right-hand shapes have or do not have a point. Below, I list the interplay between the presence and the absence of a point in this grammar based on the rule from Figure 4745.

R5-1



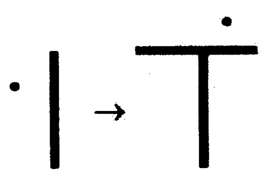
A rule where the left-hand shape and the right-hand shape have the same point location suggests locating the new thread in a cyclical fashion.

R5-2



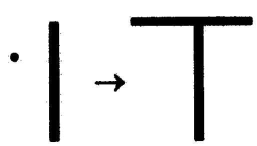
A rule where two points exist in the right-hand shape and one point in left-hand-shape, in the original and new location, provides options to add the thread in two locations.

R5-3



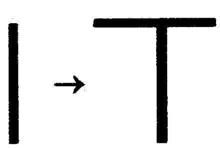
A rule where the original point is moved, instead of copied, to the new location, signifies an action to add the new thread only in the new location.

R5-4



A rule where the left-hand shape has a point but the right-hand shape does not have a point anticipates an action to end the computation process at the next step.

R5-5



A rule where neither the left-hand shape nor the right-hand shape has a point liberates the user to place the new thread in any place where the shape matches the rule.

Finally, with sets of rules in the grammar, a specific weaving style can be determined with rule sequences (Figure 5553). For instance, with two rules, A and B, the rule iteration can be controlled, for instance, A-A-A-A or A-B-A-B, to develop a certain style. Figure 5654 shows how these rules could help analyze existing interwoven structure from the past, in particular, Reciprocal Frame.[131]

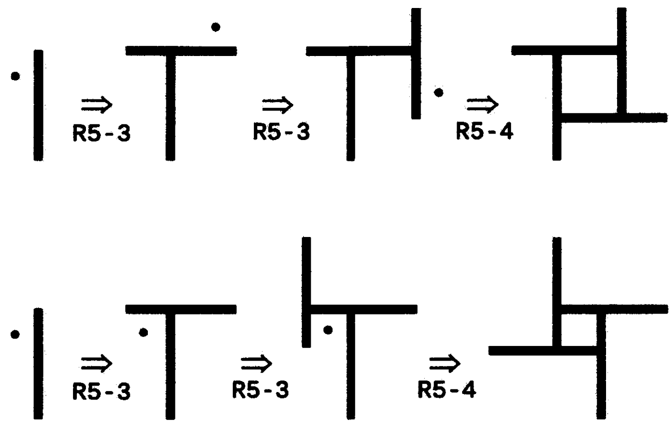


Figure 54. Where to add a new shape?
New shapes are added in different ways with a deterministic rule.

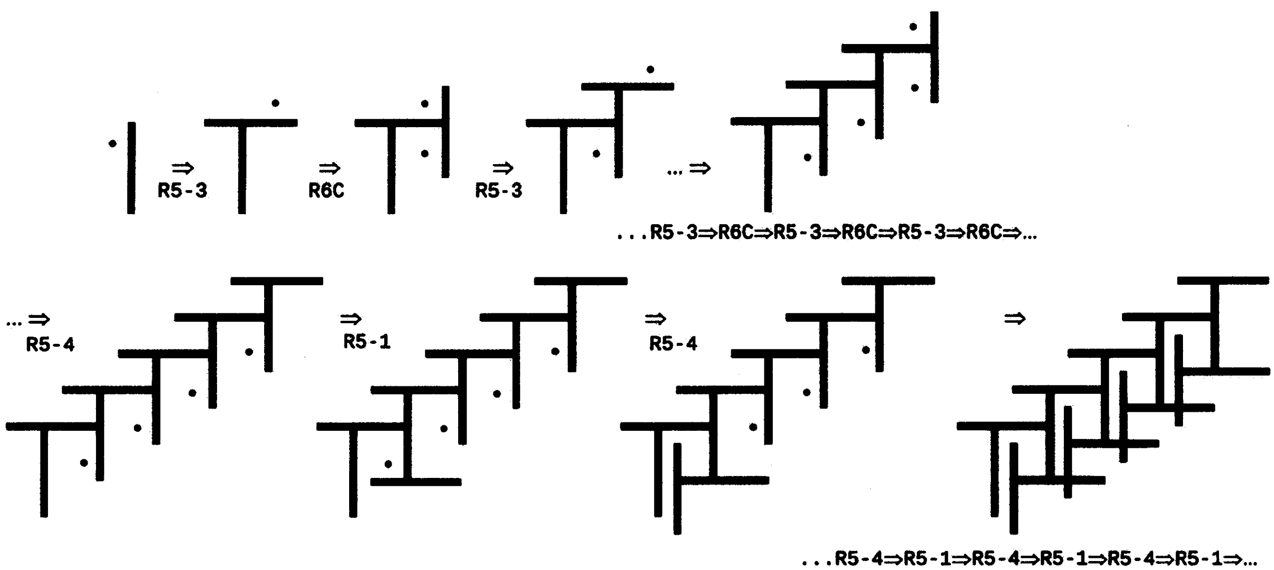


Figure 55. Rule Rhythms
Different rule sequences create specific weaving styles

[131] More detailed study of Reciprocal Frame, which inspired most of the examples of this basic weaving grammar exercise, can be seen in: Olga Popovic Larsen, *Reciprocal Frame Architecture,* 1st ed. (Architectural Press, 2008).

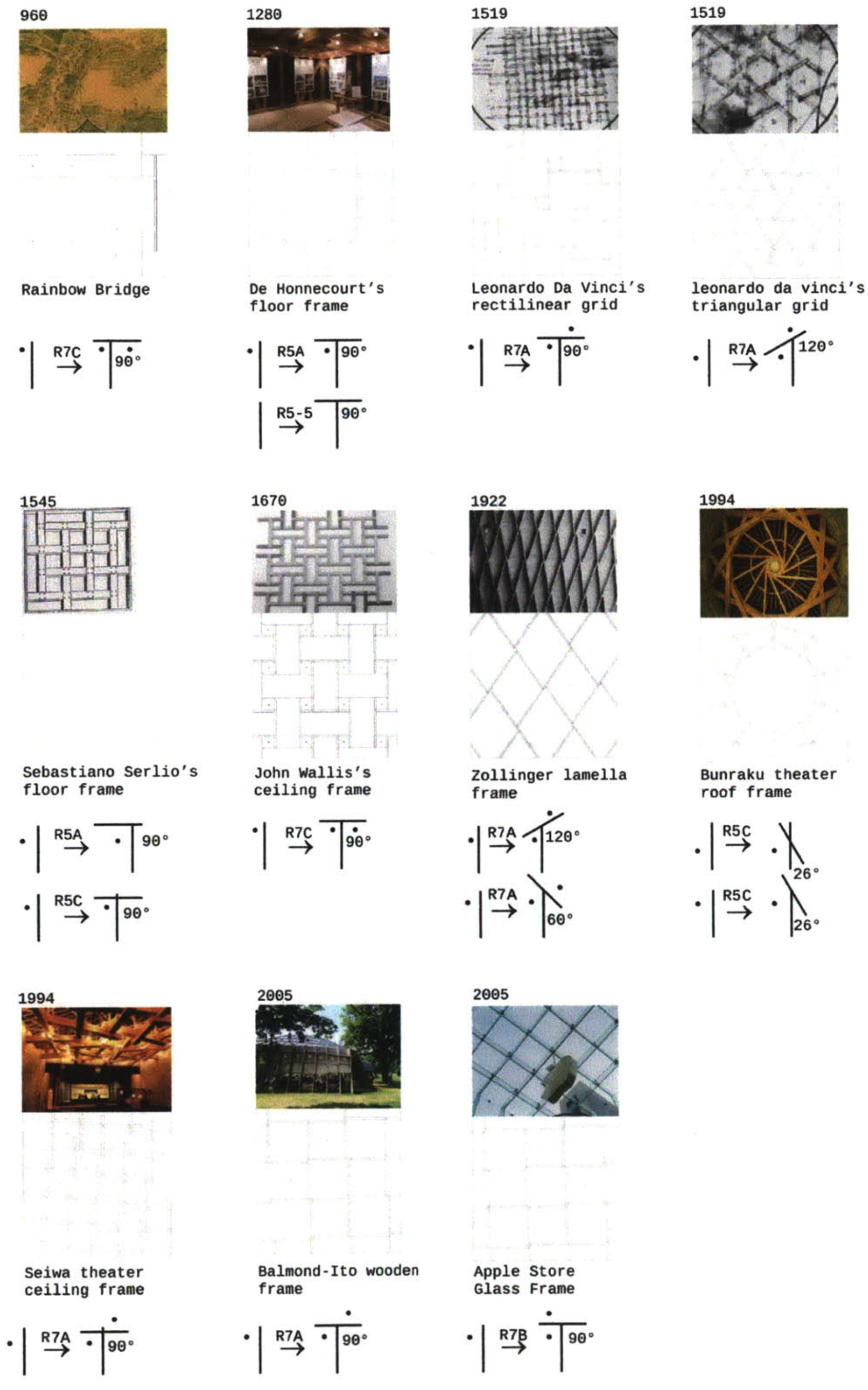


Figure 56. Analysis of Existing Design [132]

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[132] Photos on top of each generated designs are from: Ibid. and Nexus Journal, Vol. 10, Issue 1, April 2008. www.nexusjournal.com/volume-10/number-1-april-2008.html

Case Studies

This section illustrates Basic Weaving Grammar contextualization for architectural weaving in traditional context, through a series of case studies. In contextualizing the grammar, the case studies seek to investigate the process of building a tradition rather than simulating a traditional building as a product – in particular, a tradition that emerged from the assimilation between computational and traditional method.

Several considerations in contextualizing the grammar for this assimilation are examined. First, the weaving grammar needs to be easily comprehended. Second, the design must meet certain structural and fabrication requirements. Third, the rules for design and construction must be affordable with respect to the local skill and technology. To examine these considerations, I conducted three types of case studies.

Weaving Grammar Workshop: This workshop examined Weaving Grammar's degree of comprehension. The workshop was conducted in two places: Toraja, Indonesia and Cambridge, USA. In Toraja, I taught Weaving Grammar to a group of 5 craftspeople with visual media (pen and paper). In Cambridge, I taught Weaving Grammar to a group of elementary students with a physical model: a small wooden-beam (This wooden beam serves as an example of architectural weaving component.)

Structural Simulation: This simulation analyses and optimizes the structural behavior and soundness of the architectural weaving component. The simulation uses a digital model with Finite Element Analysis software and a physical model that undergoes a compressive test.

Mock-Up Installation: The installation process assesses how the weaving grammar and the fabrication process interact during the construction process. Particularly, I assess the way in which the grammar's rules assist the builder in assembling the physical component into architectural design. For this installation, I taught three local builders to build a mock-up installation. The installation was built using timber from the local site.

Study 1A: Weaving Grammar Workshop I – Measuring the Weaving Grammar Comprehension

The participants in the workshop included five local engravers in Kete Kesu, Toraja. To these participants, I first explained the background of the workshop, which was based on my observations of their colleague (the weaver whom I had observed previously). I showed them an example of how to compute the rule in the grammar using tracing paper and pen. The rule used in this workshop was R 7B, with an option to change the angle (α) of the shape relationship in rule R 5.

One of my concerns about this workshop at the beginning was that embedding and transforming the shapes using the symmetry principle would be unfamiliar for the participants. However, in the practice session, the participants were less confused about this and more troubled by how to use the tracing paper. Tracing paper is not a local commodity and thus they were not used to using it. After I showed them the benefits of the paper's translucence --. that the see-through quality was its key feature, and that they could explore embedding and transforming shapes with it -- their troubles were resolved.

Once the participants understand how to use the media, they quickly grasped how to compute the rule properly and could generate designs from rule R5. After executing the rule for a while, the participants began to improve on ways to use the media. For instance, while I usually match the shape during the iteration process by moving the tracing paper with my hands (to align the overlaid shape), the craftsmen embedded the imaginary rotation axis into the pen, as a hinge to rotate the paper.

I found later that the Euclidian transformation and symmetry principles are not new to them (although they may use it with a different term). The engravers seemed to have been using the symmetry principles in their ornament-engraving activities. Although their ornamentation rule is not visually documented, the fact that most of their ornament can be generated with rotation and symmetry infers that they may use the Euclidian transformation tacitly.[133]

[133] For more detail example on the geometrical principle of the local ornament and the rule interpretation of the ornamentation method, see Rizal Muslimin, "Decoding Passura' – Representing the Indigenous Visual

Thus, for them, this workshop was essentially a continuation of their crafting activities routine, but with different shape. At the end of this workshop, the result showed that the local craftspeople can easily acquire an understanding of the visual weaving rule and generate certain designs from the grammar.

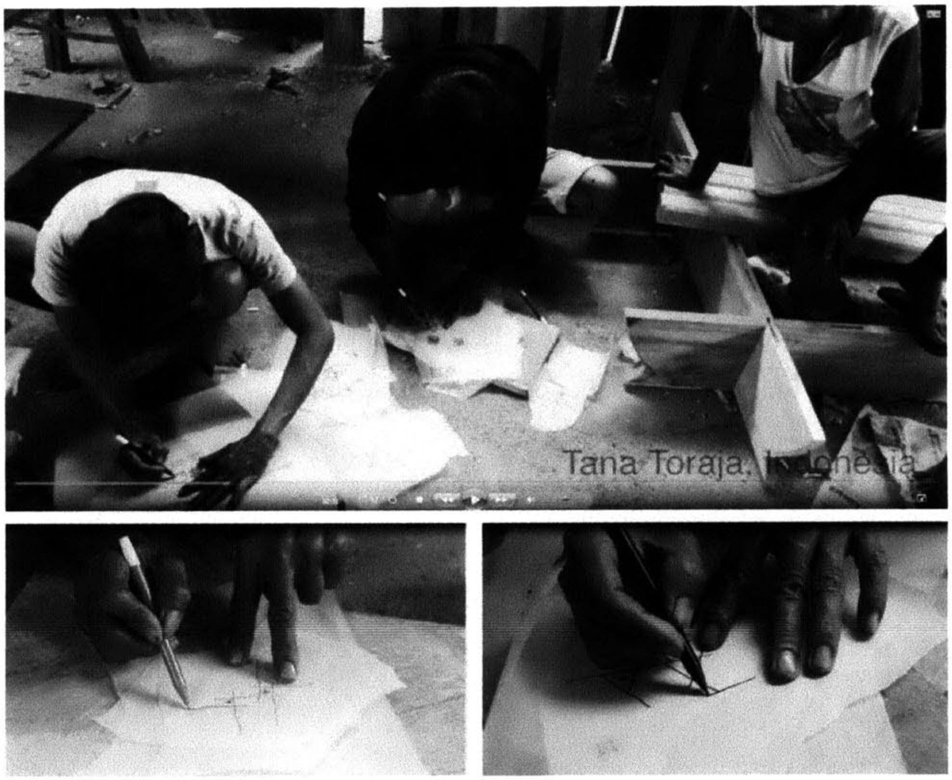


Figure 57. 2D Computational Weaving Workshop
Local craftspeople generate design from the weaving grammar

Study 1B: Weaving Grammar Workshop 2 - Setting Up the Playground Rules

The previous study demonstrated that craftspeople could generate designs from Weaving Grammar with tracing paper and pen. In this study, I conducted a grammar workshop with groups of 90 middle-school students to examine how the students could comprehend the weaving grammar with the 3D shape. [134] The study uses R 7A, R 7B and R7C.

Messages Underlying Traditional Icons with Descriptive Grammar," in *Open Systems* (presented at the the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013), Singapore: Southeast University Press Pub. Date:2007-10-01, 2013), 781–90.

[134] As part of the MIT Science, Technology, Engineering, and Mathematics (STEM) Summer program.

In the workshop, a wooden beam was used to represent the 3D physical translation of a 2D line. The weaving grammar adjustment from paper to wooden beam is described below in terms of point reference and matching processes.

Point in 2D – Point in 3D

While the rotation point helped the participant in study 1A compute the rule in the previous study, in this 3D case, it would not be effective to ask the school children to imagine the rotation point in the space between the wooden beams. For the point to be effectively used, I projected the rotation point orthogonally onto the side of the beam. As an oblong, the beam has an order of symmetry of eight. Yet, Rule R6 copied the point onto the other location of the beam using the order of symmetry 4 (Figure 5856). In other words, the beam's order of symmetry of eight was reduced by four. By this reduction, the rule only allows four ways to transform the beam in the 3D space.

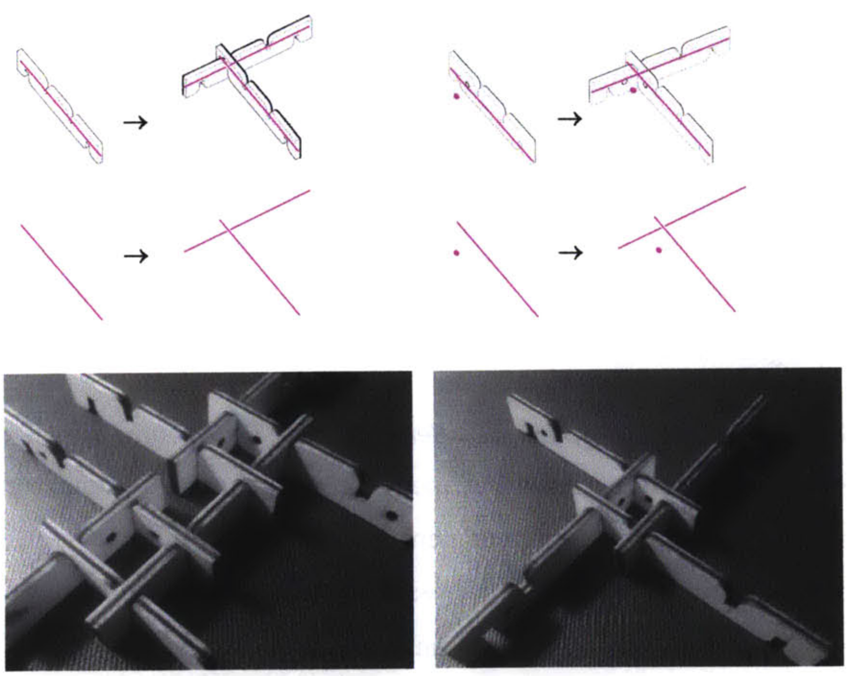


Figure 58. 2D shape is translated into physical 3D shape.

Matching in 2D – Matching in 3D

In study 1A, superimposing 2D shapes with the tracing paper accomplished the matching process. With a wooden beam, however, this process is impractical. So, to bypass the 2D matching process, the position of the two beams was fixed by interlocking joinery. Each beam has four notches to allow it to be interlocked with the other beam via one of the notches. By interlocking one beam with another, the position of two beams is guaranteed to match the shape-relationship in the rule.

With the rule's parameter embodied firmly into the shape through points and notches, the rule for the wooden beam is no longer parametric. The user can no longer modify the angle parameter (α) and the rotation point as shown in R5 (Figure 4543). Nevertheless, the beam has an order of symmetry of four, which means, even without the parametric variable, two beams can still be assembled in four spatial relationships. These options are important to explaining the generative aspect of the rule in the workshop session.

Workshop Sessions

The workshop was divided into two 1-hour sessions for students in the 5th through 9th grades. For the first session, sets of wooden beams (1 cm x 6 cm x 0.3 cm) with embedded points were distributed to the students. Each student had one set of twenty-four wooden beams. The students were presented with visual instruction (on an overhead projector screen) showing rules 7A and 7B. The students were asked to assemble a shape based on the two rules shown in Figure 5957. No other instructions, such as step-by-step images, video or demonstration, were given; the only instructions were the images of the two rules. In this way I could assess how the visual rule and the beam, with minimal instruction, helped the students create the desired designs.

After about 20–30 minutes, most of the students were able to follow the rules to generate the desired design (Figure 5957). The fixed embodiment of the rule's parameter in the beam helped the students to compute the shape in two ways: First, the notches constrained the shape-relationship, thus simplifying the matching process. Second, the point position on the beam helped the students to navigate where to place the beam according to rule R7 (Figure 5957).

For the second workshop session, another set of wooden beams, with no points, was distributed to the students. Without points, the rules become non-deterministic and the students could choose their own ways to assemble the beams. The students were given three non-deterministic rules (on an overhead projector screen) representing three different spatial-relationships, as shown in Figure 6058.

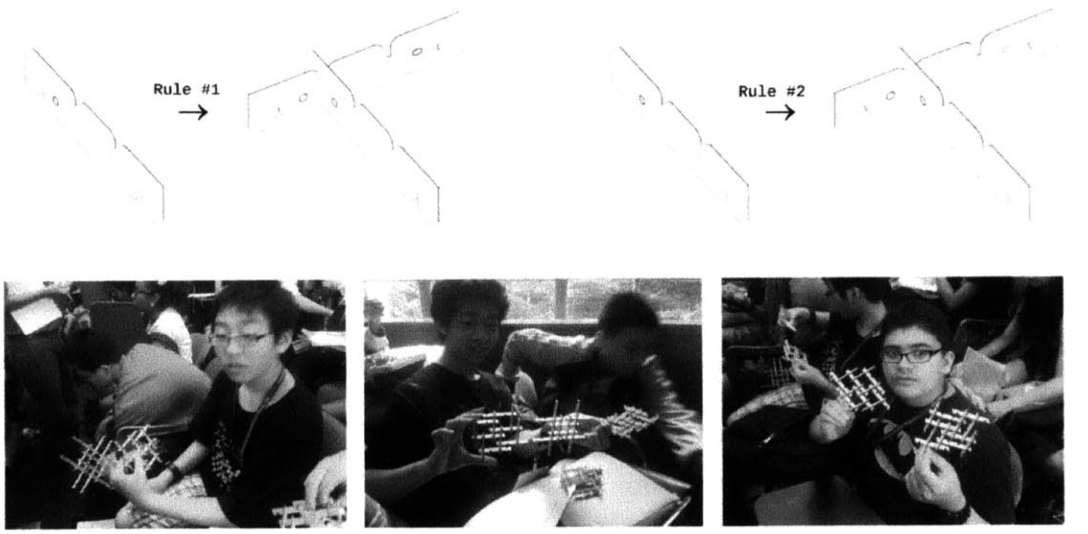


Figure 59. 3D Weaving Workshop –Session 1: Weaving with rule
5th – 9th grade students were able to generate designs following the deterministic rules.

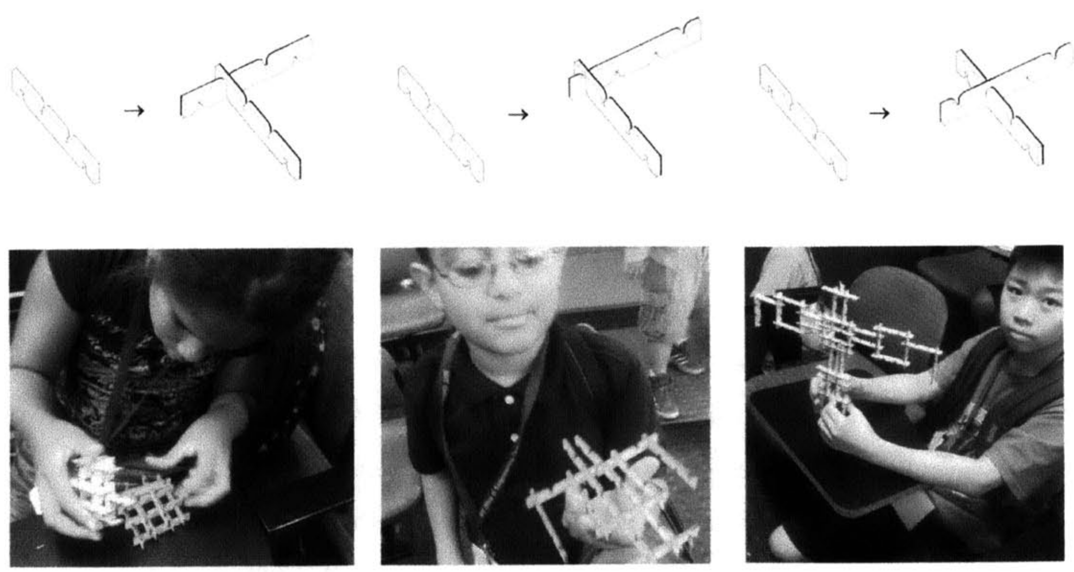


Figure 60. 3D Weaving Workshop – Session 2: The No-Rule Session
Students generated 'free' designs based on the non-deterministic rule.

During the second session, the 5th – 9th graders seemed enthusiastic about developing their own design with the shapes (Figure 6058). In their playful designs, the students tended to use the generated design pattern as an internal structure of certain objects, such as an airplane or robot. This tendency implies that some students understood the inherent structural feature of this configuration. Other students created rather abstract shapes that did not seem to aim for a familiar object, but seemed to be an exploration of how the shape could be assembled without rules. This exploration indicates that the students had found new emergent shapes and new potential for the shapes.

Study 2: Structural Simulation – Evaluating a Design's Structural Integrity

The two previous case studies illustrated the grammar's ease of comprehension. Both adult craftspeople and middle-school students had no significant difficulty understanding the Basic Weaving Grammar. These case studies indicate that Weaving Grammar's methods of designing and developing architectural weaving computationally are accessible to different members of society.

To ensure that the designs are not only comprehensive, but also applicable on an architectural scale, this study tests designs from the weaving grammar for their ability to withstand structural loads. Tests are carried out using two optimization strategies. [1] Parametric Optimization for the beam as architectural component. [2] Grammatical Optimization for an assemblage of beams as an architectural design composition. Parametric optimization tests the design's structural performance by changing the beam's dimension, specifically, the positions of the notches in the beam. Grammatical optimization tests the design's compositional performance by changing the rule within the same grammar.

Parametric Optimization for the Beam

The first test seeks to find the optimal distances between the notches, which would be loaded by other beams, to meet both structural and fabrication requirements. In terms of structure, the notches' distance should have a relatively small displacement and small stress. In terms of fabrication, the notches' distances should provide enough space to allow a builder to assemble and maneuver the beam easily.

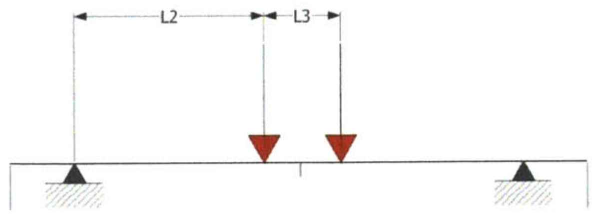


Figure 61. Idealized model for structural simulation

The Principle of Equilibrium signifies that the distance between supporting-notches and supported-notches (L2) is linearly proportional to the external force, but inversely proportional to the external forces (Figure 6159). Thus, larger L2 means lower stiffness but more space for assembly, while smaller L2 means more stiffness but less space for assembly.

To find the optimal distribution between these contradictive conditions, I tested five idealized models under different load distributions, to examine the displacement patterns using Finite Element Software (ADINA, Inc.). The left column in Figure 6260 shows the result of the Finite Element Analysis simulating the shape-displacement of five different notch distances given the external loads (Figure 6260). Model 2 from the simulation shows a smaller displacement and the lowest maximal stress.

Figure 6361 shows the how notch distance affects the design when the beam is assembled into on a larger weaving pattern. Models 1, 2 and 5 were generated using rule R7A into an interwoven pattern. The resulting pattern was then compared to assess how the optimized load distribution and displacement are related to the pattern aesthetic on a larger scale. In Figure 6361, the comparison of three models shows pattern A, which has the widest notch distance, and pattern C, which has the narrowest notch distance, are not recommended for structural reasons. Pattern B, which has the lowest maximum stress and displacement, meets both preferred structural stiffness and fabrication requirements.

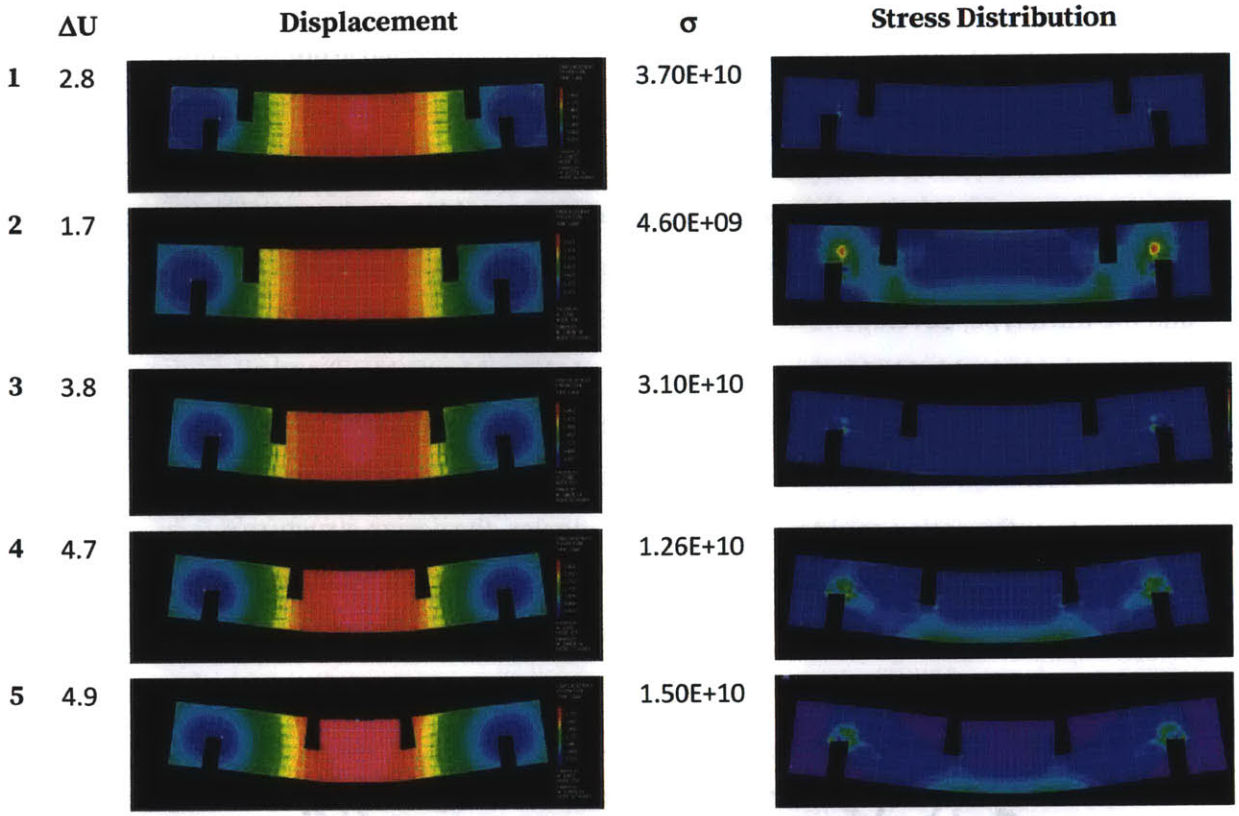
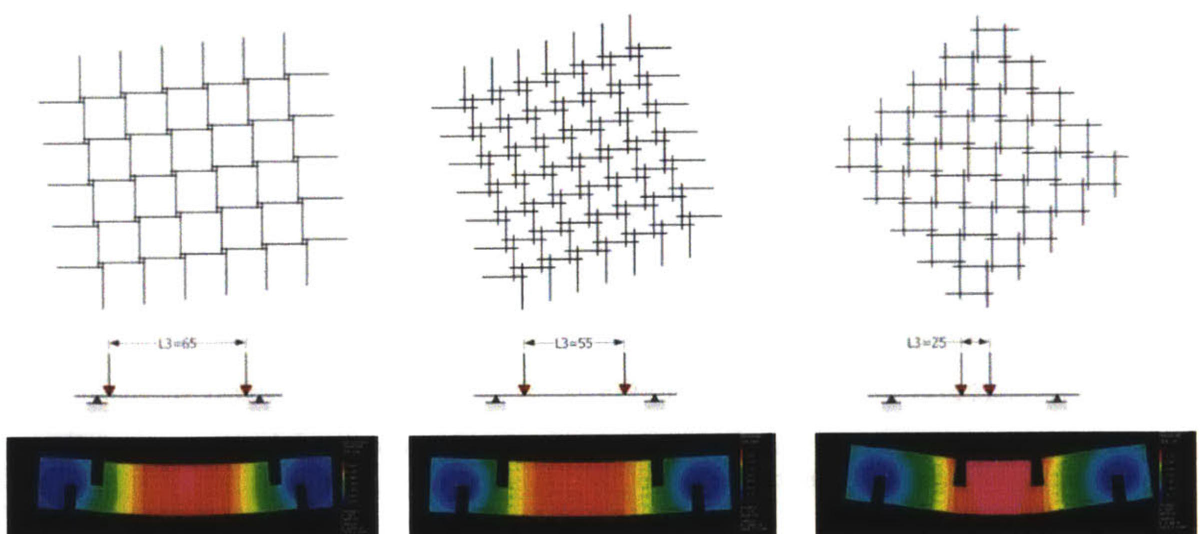


Figure 62. Displacement and Stress Distribution from five notch locations
Maximum displacement and maximal stress tend to increase as the distance between the notches narrows except model 2 (second from the top).

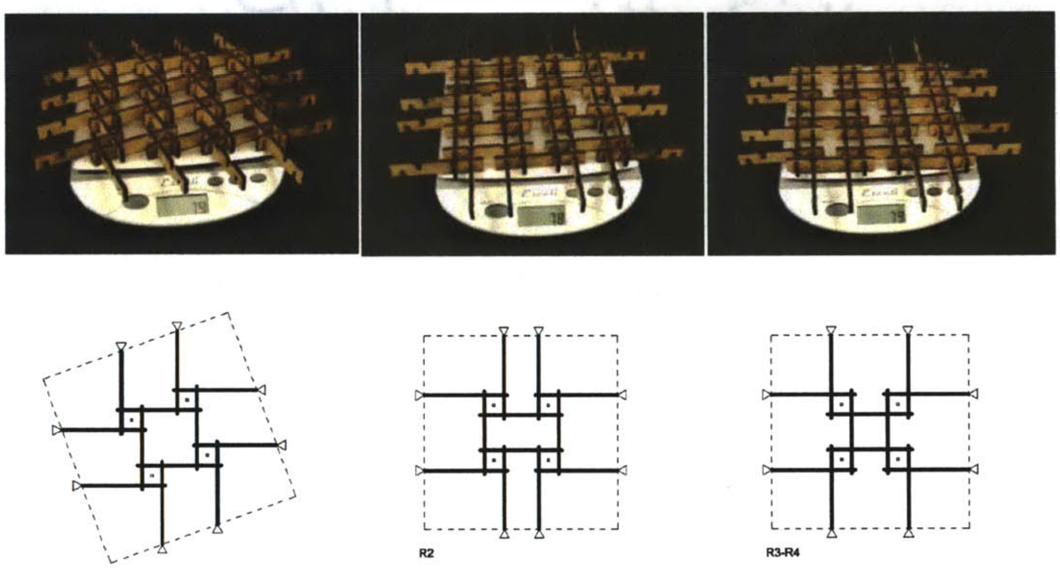


A. Not Preferred B. Preferred C. Not Preferred

Figure 63. The diagram shows the effect of load distribution on the design pattern generated with one rule: R7A.

Grammatical Optimization for a Design

Given the optimal notches for individual beams from the parametric optimization, the next test aims to find the optimal beam configurations based on the design generated by the grammar. Three models using the same beam (model 2) were generated from the grammar. The first type, developed with R 7B, is named the 'da Vinci grid', the second type, developed with R 7C, is named the 'Wallis grid', and the third type, developed with R 5B and R 5D, is the 'Nandong' grid. All three were assembled with 24 pieces of Medium Density Fiberboard (MDF) and all weigh 79 grams (Figure 6462). The assembled beams were compared using the universal test machine to examine how much external force each design's structural configuration could withstand. In particular, the design structure's stiffness was measured by the deflection of the structure under a specific load. These structures were tested in two orientations, vertical (a wall) and horizontal (a floor). Each of these grids was then loaded with 40-newton pressure force,



"da vinci grid" "wallis grid" "nandong grid"

Figure 64. Three models of interwoven beams of equal volume and weight are generated from three rules in the grammar.

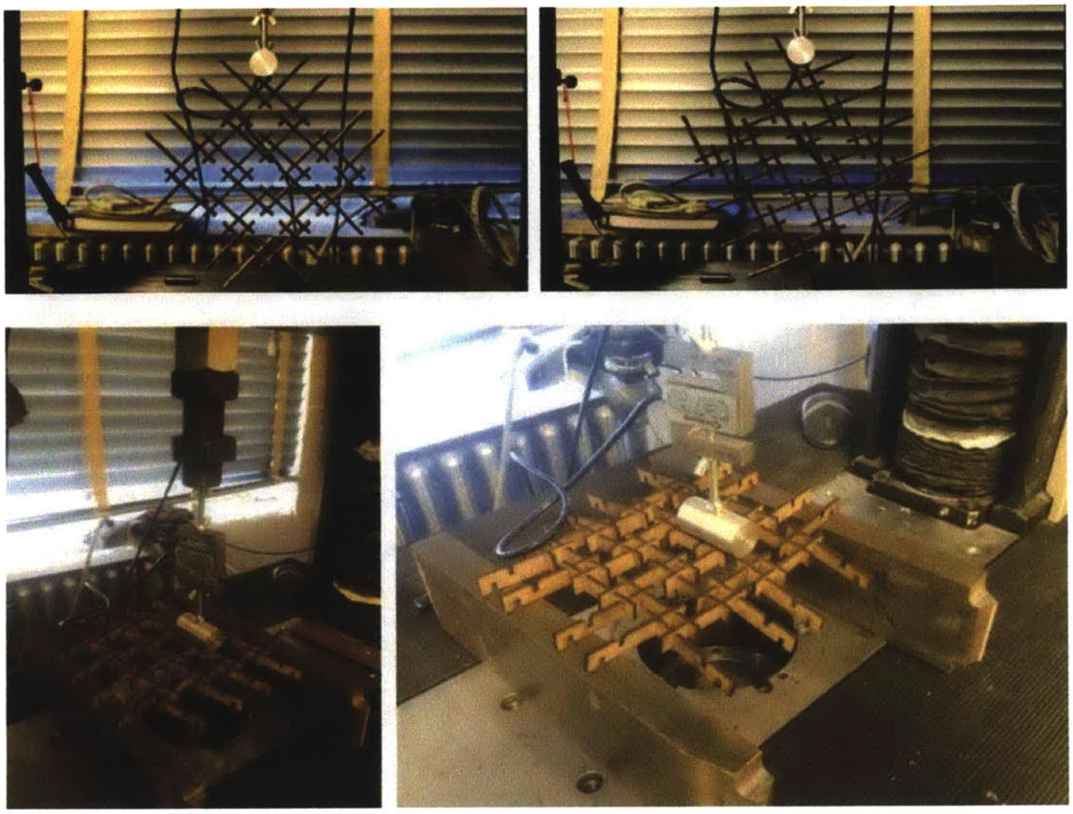
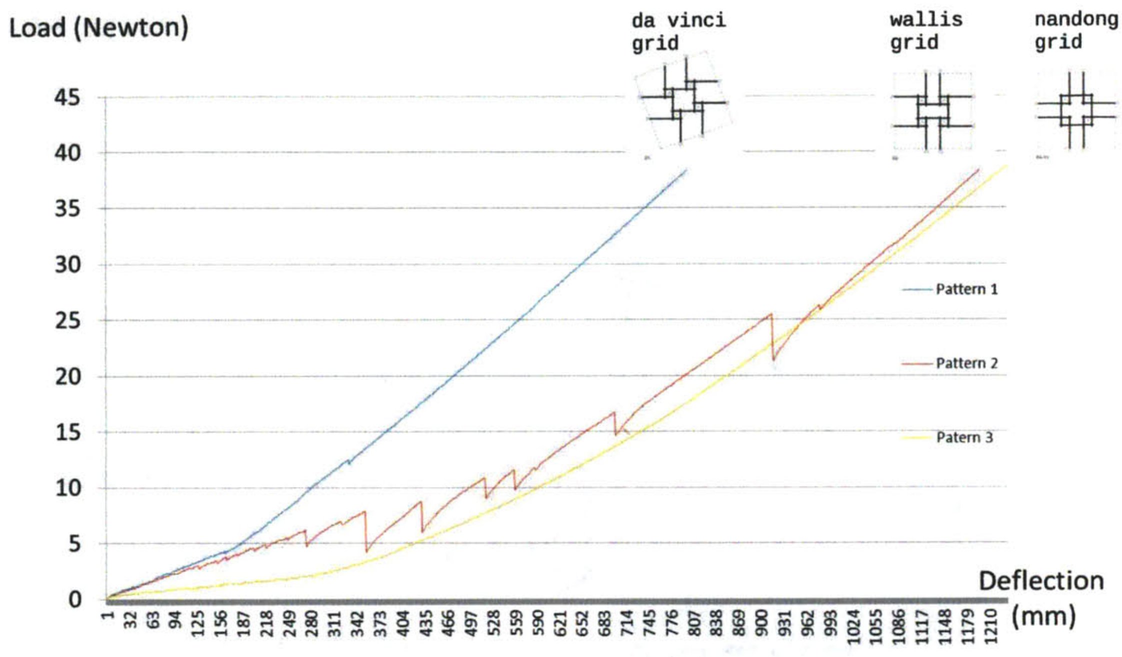


Figure 65. Optimization Test and Weighting (vertical and horizontal)

From the simulation results, in the horizontal orientation, the da Vinci grid has the lowest displacement at about 7 mm, followed by the Wallis grid (11 mm) and Nandong grid (12 mm). When placed in a vertical orientation, the da Vinci grid again has the lowest displacement with a 5.6 mm displacement, followed by the Nandong and Wallis grids, whose levels of displacement were close (Nandong 8.7 mm, Wallis 9 mm)(Figure 6664).

In Figure 6664, the jagged line on the Wallis graph (representing the floor) and the da Vinci graph (representing the wall) indicates that some of the beams had cracked. As the compressive load rose, the number of cracks increased, which means the number of solid beams structurally, supporting the increasing load also decreased. Yet, because the grid interlocked using independent beams, the crack of one beam did not spread immediately to the other beams; it remained isolated for a certain period at least. At the end of the test, none of the models had collapsed after the pressure force reached 40 Newton for both the wall and the floor.



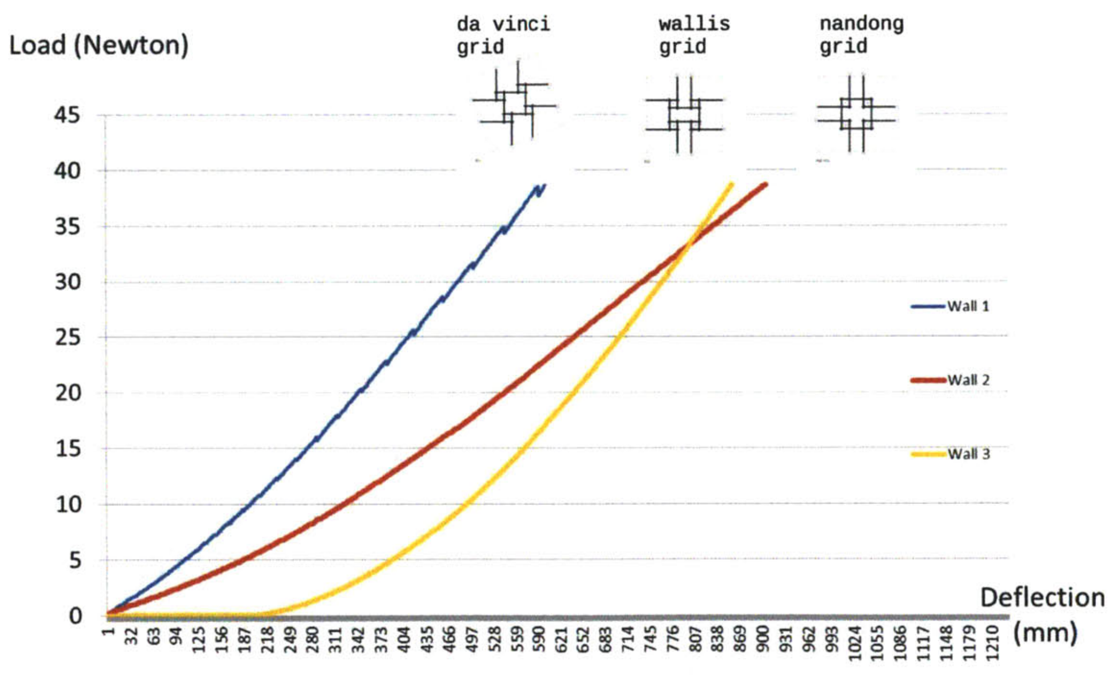


Figure 66. Results from Compressive Test
The top graph shows vertical orientation (wall) loading while bottom graph shows horizontal orientation (floor). The da Vinci grid has the lowest deflection compared to the other designs.

Study 3: Woven-Timber Installation – Envisioning the Grammar on the Vernacular Context

The previous studies showed that physical models of designs from the grammar were structurally sound and that the grammar was easily comprehended. In this study, to inspect how the shape and the rules could be applied in an actual construction project, I built a mock-up installation in Toraja. The installation involved the work of three carpenters from the local village.[137]

The 2m x 3m x 2m installation took the form of a gabled house using the da Vinci grid.[138] It was assembled near the entrance to the village using timber from local material. The 10 cm x 60 cm x 3 cm beam were manually fabricated by the local carpenter with conventional woodworking tools (saw, chisel, hammer and wood-shaving tool) based on my design. In total, 135 timber beams were fabricated for this installation.[139]

In this shelter mockup, the beams' assembly did not require additional binding components such as nails or screws and bolts, because, with four notches, the wood serves both as an element and a joint (body-joint system). In a way, the interlocking mechanism resembles the traditional weaving principles.

The positions of the notches on the wooden plank provided information to the craftsperson as to how the piece of wood should be joined. At first, a problem arose during the installation, involving adding the last piece of wood to make a closed-loop knot (the fourth beam). The first three of the four beams could be assembled as most wooden structures are traditionally built, by stacking one over the other. This was achieved by placing all the notches in one direction (all up or all down). However, the fourth beam in this case needed to be *woven in* so that the shape-relationship between the beams would extend both *over* and *under* (This is why the notch positions face both up and down.) In weaving, a new thread is added by sliding the thread in between the knotted threads. To adopt this

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[137] At the project's start, more craftspeople were ready to help, but we found that the installation did not require that many people.
[138] In this case the installation was purely experimental; the aim of it was to enable my observation of the assembly process and not for shelter purposes
[139] Note that the beams' fabrication and assembly took place in different areas. This section focuses only on the assembly part.

weaving gesture, the notches are chamfered and require a rotation movement as the assembler slides one piece of wood over another. After I showed the carpenters how to weave the beam together using the chamfered notches, the carpenters readily understood the method and could easily assemble the timber slats.

The 2D weaving rules helped the carpenter to weave the beam with minimal instruction and no construction drawing. In addition to the rules, the carpenters used a scaled model of the shelter that I made. The scaled model was assembled with the same rules and methods (Figure 6765). The model directly guided the carpenters not only in visualizing the final design, but also in understanding the way the beams were to be assembled. In other words, the fabrication method was embedded in the model just as the weaving method was implicit in the interwoven crafts.

The three carpenters started the installation around 10:30 am, and finished at 5:30 pm. I had not expected the installation to be assembled in just one day, with only three people; it usually takes a few days to assemble 135 pieces of wood (Figure 6866). Later, one of the local craftsmen explained to me that their ~500-year-old traditional houses were also assembled with wooden joints that do not require nails. The wooden slats of these houses are notched, thus the body-joint system was familiar to them. Yet the beams in the traditional houses are stacked on top of the other, not woven. The difference between the traditional houses and this installation is that, in the case of the installation, the timbers were woven with principles inspired by the local weavers. Thus, somehow, this installation married their ancestors' construction techniques with their colleagues' crafting techniques.

Figure 67. A carpenter holds the scaled model during the fabrication process to verify where to place the timber.

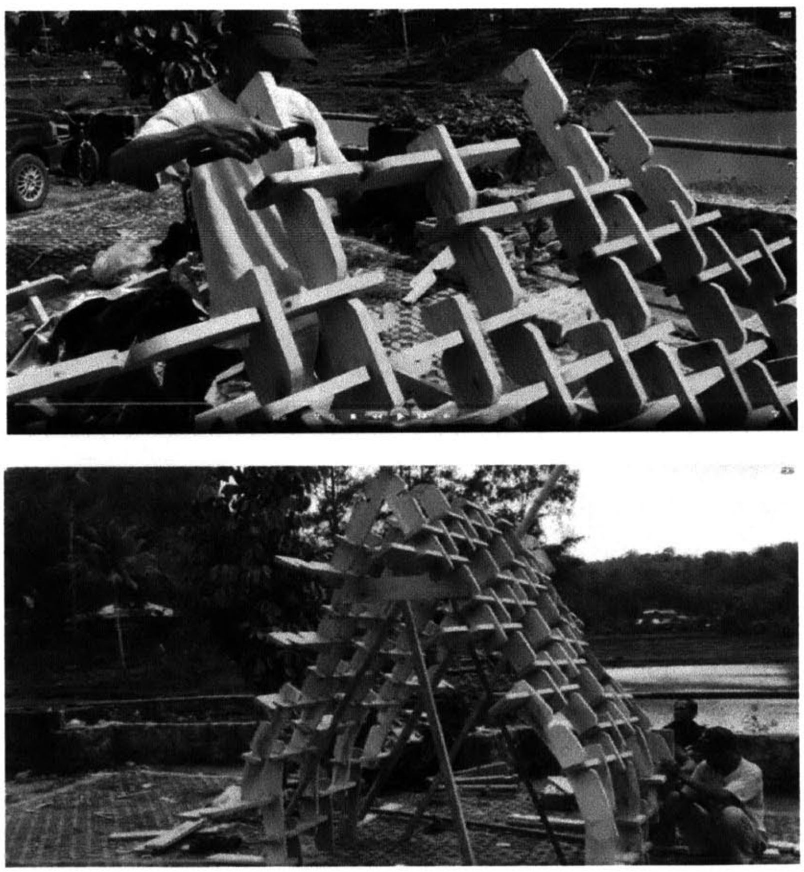

Figure 68. The Mock Up Installation

3.3 Abstract Weaving Grammar: On Extending the Language of Weaving Design

Introduction

This section explains the process of reinventing weaving with abstract weaving grammar—a set of rules that can generate new designs by reconfiguring the shape's mechanical description and the shape's boundary relationship. Inspired by the traditional weaver's visual and haptic experience, my aim is to provide computational design methods that can incorporate the aesthetic-structural integrity of weaving into architectural design.

In developing abstract weaving grammar, I adapt some aspects from traditional weaving by aligning the way in which traditional weavers sense the weave with computational mechanics and computational design theory. In this alignment, I include approaches from the finite element method (FEM) into shape grammar's visual computation method to better integrate the shape's mechanical consequences with the shape's visual significances. By relying more on the abstraction of weaving mechanics properties and less on the common conception of typical weaving material, the design that results from this grammar is hoped to extend the language of weaving design.

FEM and Shape Grammar

FEM is an engineering method used to analyze the physical behavior of an object that has been idealized into a mathematical model—an assemblage of vertices, edges, and faces that define the object's shape. In this model, the object is defined by the mechanical properties of its element, such as profile area (A), length between vertices (L), boundary conditions (U), the material's degree of elasticity (E), and the applied external load (R).

Given a shape's mechanical properties, FEM decodes the mechanical behavior of the shape by satisfying the equilibrium equation (based on Hooke's Law) to solve the unknown point of displacement (dU). The internal stiffness of a bar, defined by the variables E, A, L, and dU, should be equal to the external force on each element of the shape (R), as follows:

$$\frac{E\ A}{l} dU = R$$

To incorporate FEM principles into the computational design process, shape calculation in FEM and shape grammar must be represented in the same visual language.

In the *Finite Element Method for Engineering Analysis,* Bathe describes the process of idealizing physical objects into mathematical models in four phases: geometry, material, loading, and boundary condition.[141]

> The geometry phase represents the kinematic shape of a physical object (e.g., Is the shape a bar, beam, plane stress, or 3D object?).
>
> The material phase assigns material properties to the kinematic shape (e.g., Is the material isotropic, anisotropic, elastic, or rubber?).
>
> The loading phase applies an external load onto the object (e.g., Is the load concentrated in one point, distributed evenly, linearly, or centrifugally?)
>
> The boundary condition defines the degree of freedom of the shape (e.g., Can the shape move or rotate around a certain axis)?

To better understand how this idealization process works in the context of weaving, in the following, a knot of a weave is computationally represented and scrutinized via three approaches. First, I revisit Kawabata's model in idealizing the knot into a finite-element model through shape grammar rule notation.[142, 143] Second, I compute a knot's shape with boundary rules in shape grammar, without any mechanical properties. Third, I alternately calculate the knot with the FEM idealization rules and shape grammar boundary rules.

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141 Bathe, *Finite Element Method for Engineering Analysis* (1996), 165

142 S. Kawabata, Masako Niwa, and H. Kawai, "3—the Finite-Deformation Theory of Plain-Weave Fabrics Part I: The Biaxial-Deformation Theory," *Journal of the Textile Institute* 64, no. 1 (1973): 21–46, doi:10.1080/00405007308630416.

143 Kawabata's knot schema of a bi-axial weave laid the foundation of basic research of textile mechanics in the clothing industry and has been subsequently studied and refined to include additional properties of the knot such as the spring-moment at the friction between two yarns in the Kevlar model and shear-lock in analyzing the knot's rigidity under shear stress in the King's model.

Knot in FEM–Kawabata's Schema Revisited

In this section, Kawabata's schema of knot of biaxial weave is revisited in the order of the FEM idealization process described before using shape grammar rule notation (Figure 6967).

Geometry

Rule G1 generates the parametric schema of a yarn. In idealizing the knot's kinematic geometry, Kawabata perceives the physical yarn by embedding one-dimensional weight in the knots—the *structural neutral line*, (W_{13}). Using this neutral line, the 3-D yarn is represented as a 1-D bar in 3-D space (U_{13}). Variable (L) represents the yarn segment's length and variable (A) represents the yarn's profile area.

Material

Rule M1 assigns the material property to the bar to describe its material stiffness, such as the material degree of elasticity (Young's Modulus–E). The assigned bar is represented with a color that inhabits the 1D bar (U_{13} + W_{11}). One can perceive different material properties of the bar by assessing different colors; for example, cyan means it is elastic, magenta means it is rigid. The color of the material can be further parameterized to represent a wide range of material options.

Loading

Rule L1 adds external force (F) to the endpoints of the bar, and L2 transforms the point based on the force's magnitude. The force is represented by arrow (V_{12}), to indicate direction in which the load is applied. [144, 145] While the load in 3-D space can be oriented in many directions, in the equilibrium equation, external force is calculated independently as a 1-D vector in 1-D space (U_{11}). For instance, in case there is an angular direction of the force direction, the force will be projected onto the y-axis and the x-axis.

[144] This model ignores the bending moment (M_{xz}) from a yarn segment's deformation in plane xz, and cross-over moment (M_{xy}) from a shear deformation in plane xy. For more detail about this moment, see Kings model.

[145] A label in shape grammar is commonly used to reduce the shape's symmetry (Knight), to show where to add a new shape (Knight) and to attribute identity to a shape if some shapes look the same (Stiny).

Boundary Condition

Rule B1 defines the boundary condition of the bar. The boundary condition refers to the shape's degree of freedom (DOF) in responding to the external forces (in this case, the external forces applied to the points at the end of each bar (U_{0j})). The arrow in the right-hand shape indicates the degree of freedom.

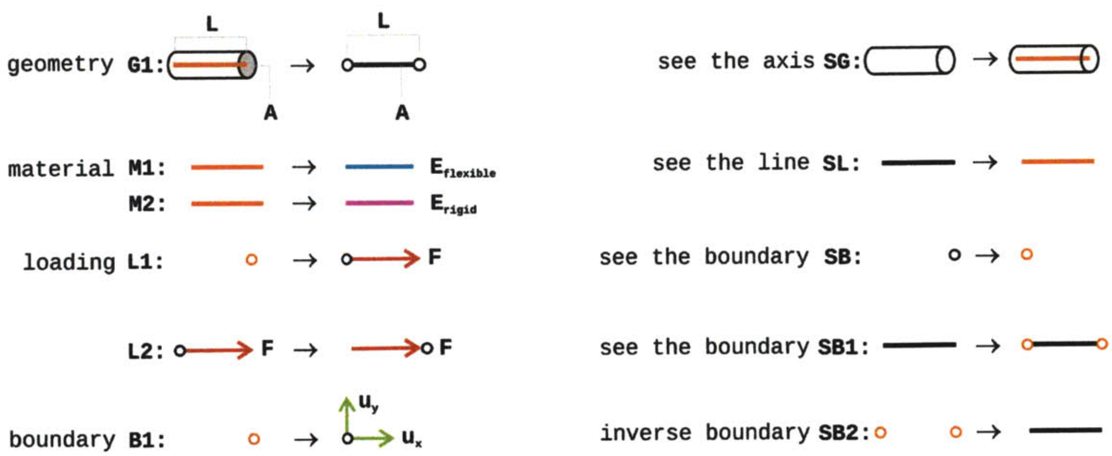

Figure 69. Rules for FEM idealization in shape grammar.

In addition to the mechanical rules, the grammar is also accompanied by the set of *seeing rules* to allow users to visually identify part of the idealized knots that would be applied by the mechanical rules. Such rules are Rule G, to see the neutral axis of a thread, Rule M to see the line, and Rule B to see the boundary of a line (point)(marked by the orange shape in Figure 6967. Together, the seeing and mechanical rules work recursively in the computation, where the seeing rules highlight the user's visual attention on part of the knot, and mechanical rules apply a mechanical description on the highlighted parts.

Figure 7068 shows the iteration of generating Kawabata's schema of a plain weave's knot using the above rules. The iteration to the far right identifies shapes that are visually attended, and the iteration in the middle shows the embedded mechanical properties of the visually attended shapes. By applying the rules recursively, four original Kawabata's schemas on the left images are generated.

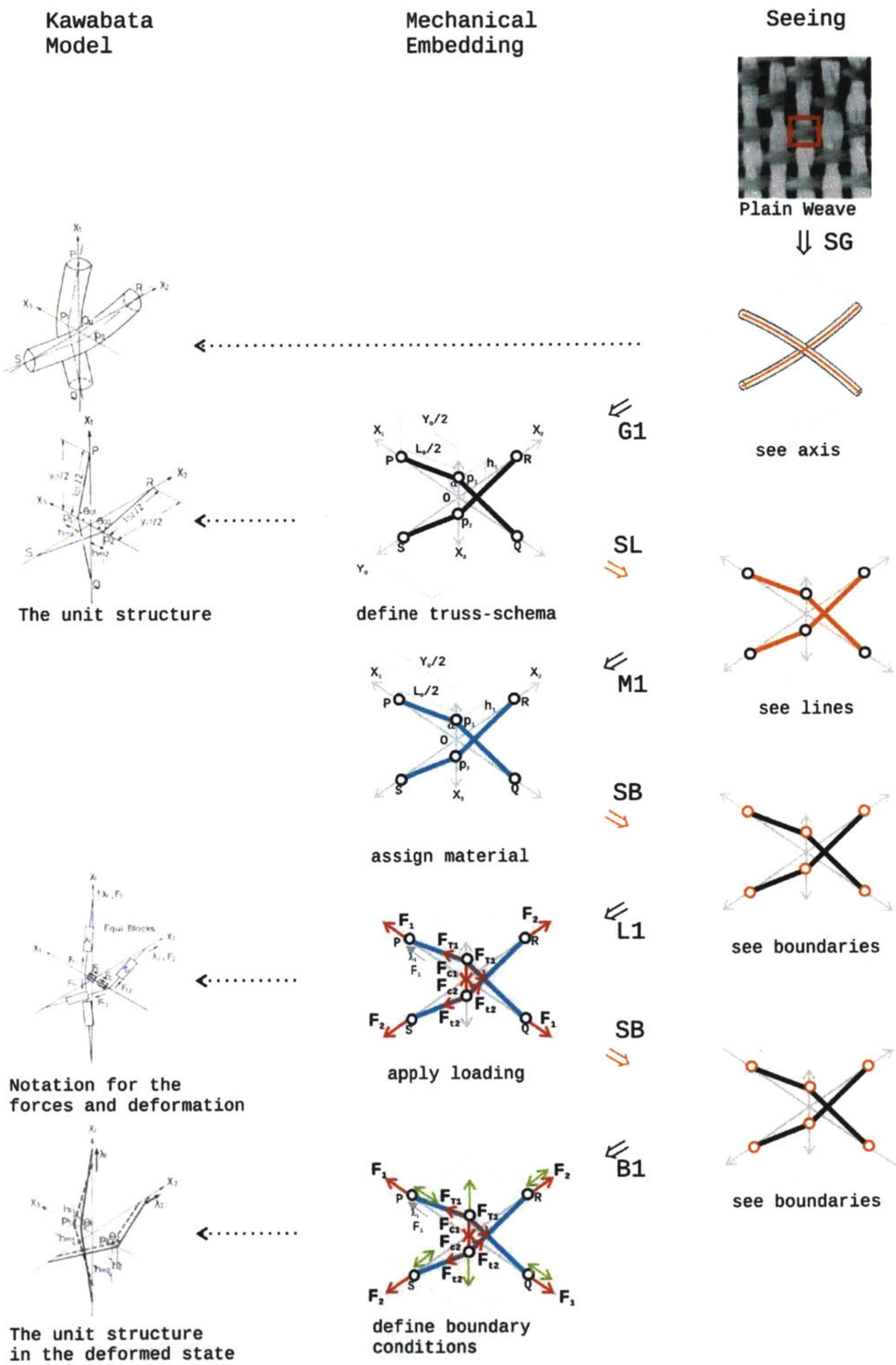

Figure 70. Kawabata's Schema Reiteration [146]

Rule derivation to revisit Kawabata's model of the knot, as a unit cell geometry of woven fabrics (1973).

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[146] Plain weave image and the original unit structure model are from: Kawabata, Niwa, and Kawai, "3—the Finite-Deformation Theory of Plain-Weave Fabrics Part I."

In this idealized mathematical model, the knot's optimization process can be performed by modulating variables in the equilibrium equation to satisfy the virtual equilibrium principles (Figure 7169). For instance, the material degree of elasticity (E) and the yarn's cross-sectional areas (A) are proportional to the external load applied to the knot (R). Thus, by increasing variable (E) (e.g., using a stiffer material for the yarn) and/or increasing variable (A) (e.g., increasing the yarn strand's dimension or density), we can increase the knot's rigidity. Additionally, because variable (R) is inversely proportional to the yarn's length (L), then decreasing variable (L) can also strengthen the knot's rigidity (e.g., by adding smaller knots within the same knot module dimension (Y)).[149, 150]

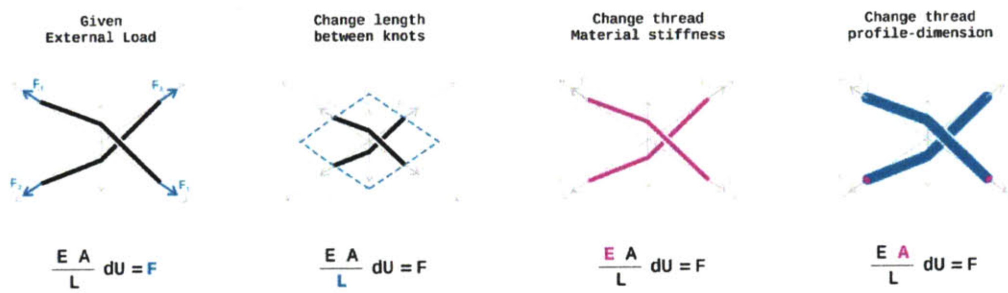


Figure 71. Variables for optimization of the knot's rigidity in the Kawabata's schema.

Knot in Shape Grammar–Boundary Rules

In revisiting the Kawabata's schema, I separated the shape of the knot from its mechanical description with seeing rules. By this separation, the knot can be calculated in shape grammar purely as a shape. In the following, I explain how shape grammar visually calculates the shape of the knot with its boundary rules.

The boundary and shape in shape grammar is not tightly bound as in the Kawabata model. Applying a boundary rule, $x \rightarrow b(x)$, to a line will produce the line's endpoints, but applying the inverse-boundary rule, $x \rightarrow b^{-1}(x)$, to the points will not only retrieve the previous line. Because the endpoints are independent from the line, the results of applying inverse-boundary rules on the point are not

149 Kawabata solved this equation by offering two conditions: One in which the yarn is compressible and another in which the yarn is uncompressible.

150 For instance, Kawabata uses this schema to analyze other weave types, such as the tri-axial weaves S. Kawabata, Mari Inoue, and Masako Niwa, "Non-Linear Theory of the Biaxial Deformation of a Triaxial-Weave Fabric," *Journal of the Textile Institute* 83, no. 1 (1992): 104–19, doi:10.1080/00405009208631180.

limited to the previous line. It can be any shape that has the points as its boundary. Similarly, in the knot, the result of the inverse-boundary computation on the yarn's endpoints is not limited to the previous overlapping yarns. It can also retrieve other lines where points coincide with the other line's boundaries.

Figure 7270 shows boundary-rules computation on a knot, where the knot is viewed from the top. With the boundary rule, shape grammar computation could generate various shapes on the knot using the yarn's original endpoints. The three iterations in the figure show the boundary and inverse-boundary rules generate new knots. Of the three, the first two steps from the rule, $x \rightarrow x + b(x)$, produce similar results—four points on the knots. For the third and fourth steps, however, the inverse boundary rule, $x \rightarrow b^{-1}(x)$, begins to show different shape compositions as a result of applying the rule only to specific points. For instance, the boundary of the four points in step 2 could be four lines (a square) or two triangles in step 3. Similarly, the inverse boundary of the lines need not be applied to all four boundary lines in the square, as the original yarns can also be considered as lines. As shown in the third row of the third to fourth step, the inverse rule is applied to two lines and the original yarn (forming a triangle) to retrieve the triangular plane (gray). The fifth step of the iterations shows a new shape where the original knot typology has been fully altered, as some lines have disappeared into endpoints as a result of applying the boundary rule to the lines.

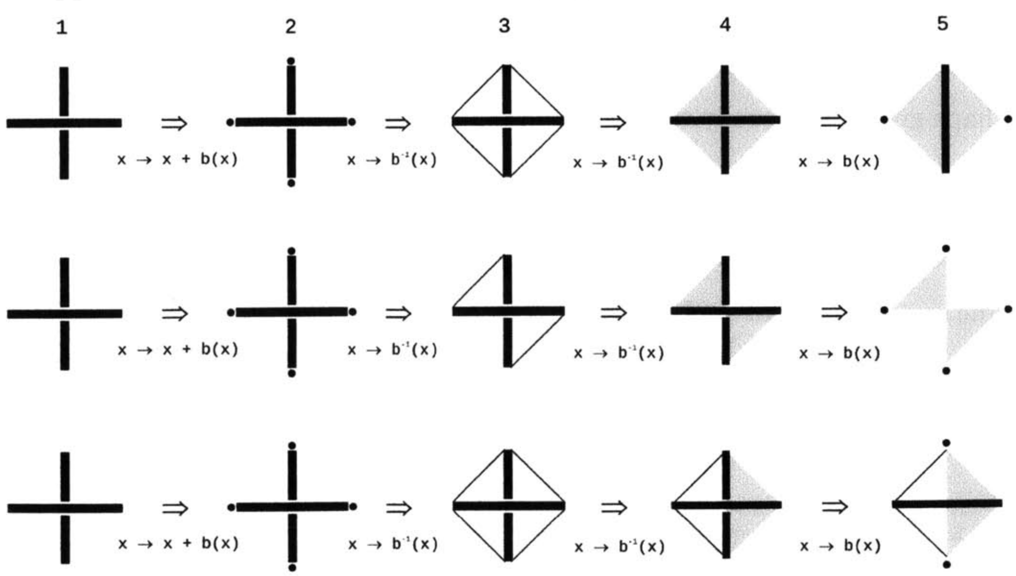


Figure 72. Boundary rule iterations.

Knot in FEM-Shape Grammar–Perceptual Optimization

The knot's calculation in FEM and in shape grammar shows a potential symbiosis in the way in which a knot is seen as a shape with embedded mechanical descriptions.

This symbiosis paves new corridors through which the way a traditional weaver and engineer optimize a knot's structure can complement each other. In particular, in the way an engineer and weaver consider the available options in optimizing the knot (Figure 7371). In conventional building engineering practice, the external force (R) is mainly considered as a given condition because the design configuration is considered to be finished. To achieve a certain degree of the knot's stiffness, the option is to modify the yarn's internal mechanical property (i.e., variables E, A, and L). For the weaver, the bamboo's material property (E) is considered as a given condition. To meet his design goal, the option is to modify the thread's shape and the external force on the knot (i.e., variables A, L, and R).

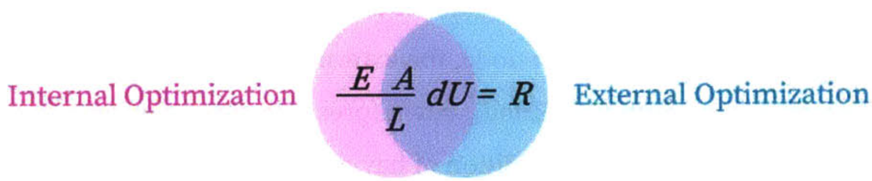


Figure 73. Different focus in in optimization between internal optimization and external optimization.

Representing these two approaches in the equilibrium equation highlights an intersection where some variables overlap while others are independent. The overlapping variables, A and L, indicate that both the engineer and weaver are keen to modify the shape of the knots. On the other hand, the independent variables, E and R, underline the strong feature of each approach. The engineer can modify material properties (E) but not the external force (R). The weaver does not change threads' material properties (E) but can modify external force on the weave (R).

By combining the features from the two grammars, there is an opportunity to achieve the weave's structure and aesthetic integrity in architectural design by modulating the thread's material properties (E) using the mechanical rules and by modifying the external force 's shape (R) with boundary rules.

The following strategies: loading, boundary, and material ambiguities, set mechanical rules and boundary rules by incorporating the traditional weaver's haptic experience in the previous chapter.

Strategy #1 - Loading Ambiguity

In the previous chapter, I described the haptic ambiguity that occurs at the moment after the material "feeds" information to the weaver's perceptual system and before the weaver decides what action to take with that information. At this moment in time, the weaver has several options as to which direction and how much muscular force he or she needs to apply to the thread (e.g., how much to pull, push, or pinch).

The strategy proposed here is to formulate the weaver's haptic ambiguity within the grammar. Represented with 6 nodes and 3 axes, the knot has 18 degrees of freedom. This means that in each node, the external force can be applied in many directions, for example, up (lifted), down (pressed), front (pushed), back (pulled), left or right (tilted). The condition of having these different options for which to apply external load is analogous to the moment when a weaver considers which way to move the thread.

Figure 7573 shows four different ways rule L1 applies external load to the endpoint of the knot. Rule L2 shows the mechanical consequences of different loading conditions by moving the knot as a rigid body (e.g., fall down, moving apart, shifted horizontally).[151] As a consequence of applying rule L2, the shape-relationship of the knot in the right column has now changed. In other words, the knot design has been mechanically derived into four new spatial relationships.

[151] As a rigid body, the thread moves to new position as a whole with a Euclidian transformation without deformation.

Strategy #2 - Boundary Ambiguity

The traditional weaver responded to the material's reaction in different ways, from various hand gestures to the use of external apparatuses such as the floor. Thus, what mattered to the weaver was that certain forces (R) that he applied to the material made the material "behave" or react in an expected way, regardless of whether he applied these forces with his body or used other external apparatuses.

This second strategy is in the way the weaver responds to the weave with different gestures by incorporating the inverse-boundary computation. Here, the new shapes from the inverse-boundary computation with rule SB1 and SB2 in Figure 7270 serve as alternative shapes to mediate external force (R) in responding to the knot's mechanical behavior. For instance, in a condition where a thread is bending down, applying the inverse-boundary rule on the thread's endpoints would produce new lines other than the thread itself. These new lines can then be used as external forces on the thread to stop the bending.

The new shapes for the external forces are parallel to the weaver's initiative to respond to the knot's mechanical behavior with different gestures or apparatuses.

Strategy #3 - Material Ambiguity

One common feature the traditional weaver and FEM principle share is that the knot's stiffness is relative. In FEM, this relativity is indicated by possibilities to modulate Young's modulus of the elasticity (E) by the ratio of stress and strain. Thus, to have a stiffer material, Young's modulus ratio needs to be higher and vice versa. In traditional weaving, the relativity is signified by the way the weaver constantly shifts his or her perception on the material stiffness, depending on his or her design and structural needs. At one point, the weaver may perceive the knot to be rigid, and at another time, flexible (see page 66).

This strategy is derived from this view on material relativity. In the process of designing the knot, the material is not absolute. It can be considered as rigid or flexible, tensile, or compressive. Rules M1 and M2 accommodate this relativity. Figure 7775 shows the color is used to encode material properties to the shape. Using color-coding rules, the user can generate different mechanical behaviors of the knot by recursively changing material properties with this rule, similarly to the way the weaver shifts his or her perception of the material's rigidity.

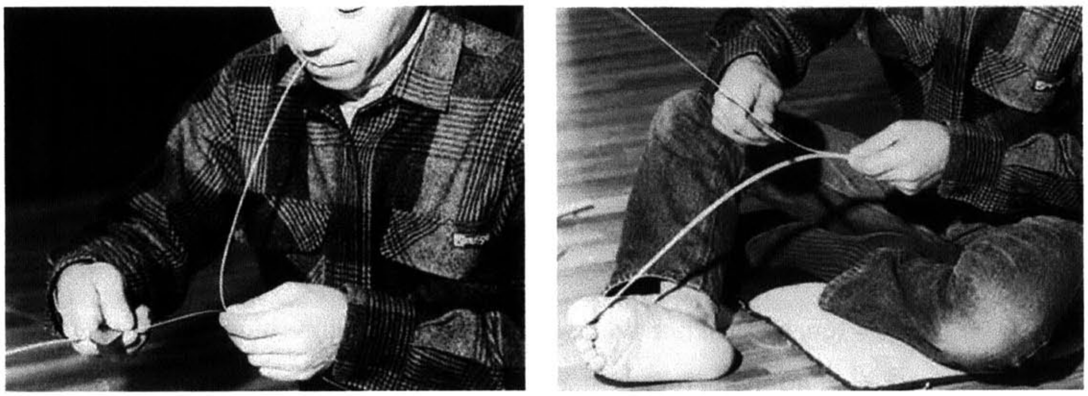


Figure 74. Instantaneous and ever changing external force by the weaver by foot-grips and mouth-press. [152]

[152] Photos from: Oita Prefecture Basket Weaving Manual

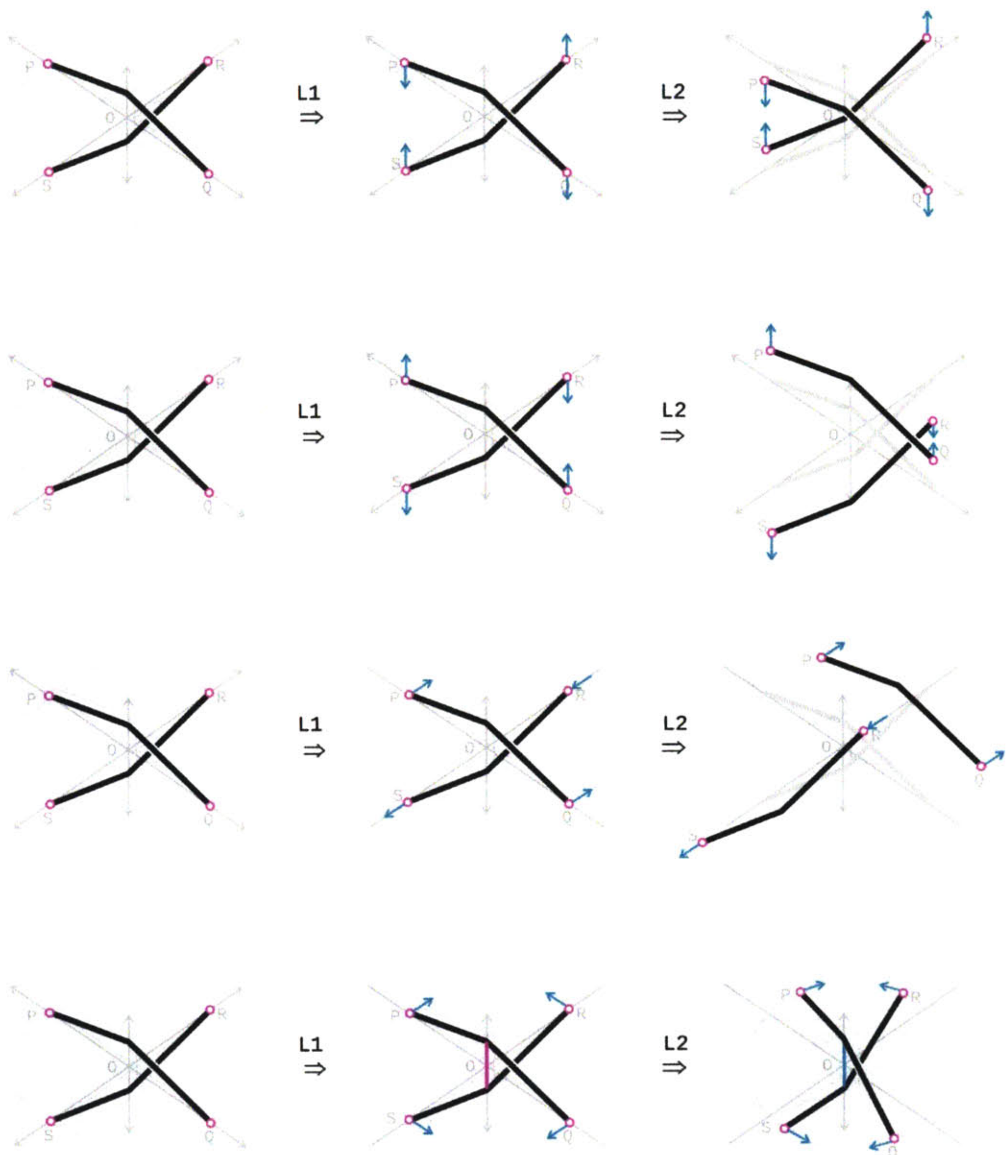


Figure 75. Loading ambiguity–new shape-relationships.
A different external loading direction is applied to the boundary of the knot with L1. L2 transforms the shape as a consequence of each loading configuration.

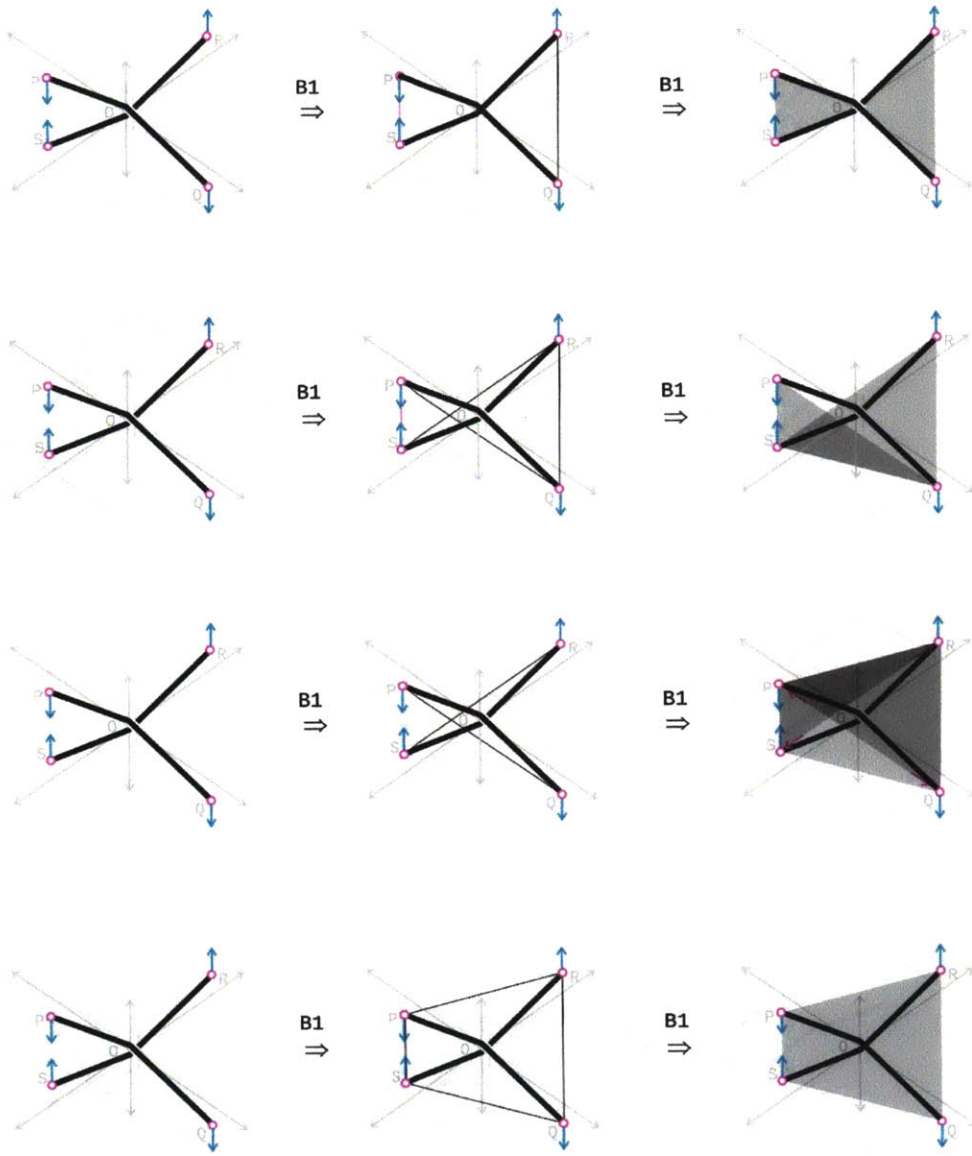


Figure 76. Boundary ambiguity–new external forces.
The inverse-boundary rule is applied to the mechanically transformed shape from Figure 7573. In the 3-D space, the inverse-boundary of four points yields a linear shape once, and applying the rule again to the linear shape yields a 3-D planar shape.

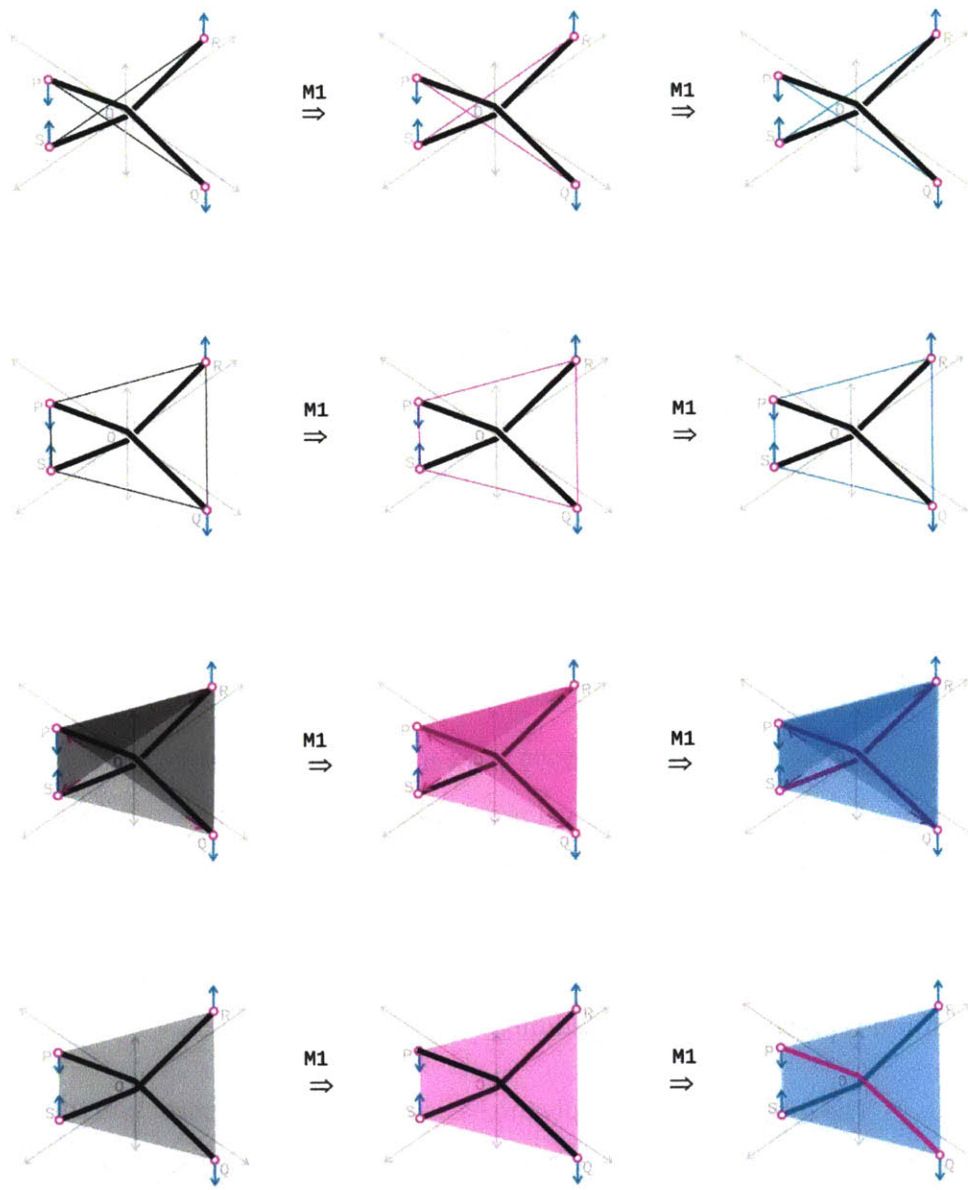


Figure 77. Material embedding–new shape behavior.
Material stiffness is embedded into the shape with coloring rule M1, recursively. In the left columns, the shape does not have a material embedded (represented with black). In the middle columns, each new shape is embedded with flexible material (magenta). In the right column, the new shapes are embedded with rigid material (cyan), and some of the original yarn is embedded with flexible material (magenta).

The Children of Weaving

Kenneth Snelson once said, "Weaving is the mother of Tensegrity."[153] In his comparative models, one can indeed see the resemblance between the type of weaves and the type of Tensegrity modules. Yet there are limited references about his design process on inventing the tensegrity modules from weaving. How did Snelson sense weaving and come up with Tensegrity? If one understands his inventing process, could Tensegrity have siblings other than weaving?

In this section, I demonstrate the way abstract weaving grammar derives new knots designs mechanically and visually. In particular, I demonstrate the way in which mechanical properties from FEM and boundary rules from shape grammars work in tandem in generating new kinds of knot. This generative process also allows us to interpret the way weaving develops into different systems, including Tensegrity.

Figure 7876 and Figure 7977 show how a knot is generated into different designs in terms of its mechanical properties. The computation provides corridors where the user could alternate between seeing the knot as a shape and as a mechanical configuration. In these figures, the middle column represents seeing rules computation. The left column represents mechanical embedding. The right column represents visual embedding.

The first three steps apply the basic mechanical properties on the knot. In step 1 and 2, rule G1 assigns the thread as a truss and rule M1 applies a rigid material description to the thread as rigid. In step 3, rule L1 applies force vertically to pull the threads away from each other. In step 4, rule B1 applies the boundary condition that allows the thread to move only in vertical direction.

In step 5, Hooke's law is applied to the threads, and as a result, the threads move away from each other. Here is where visual embedding comes into play. To respond to the knot's disintegration, rule 5B highlights the endpoints of the

[153] "Kenneth Snelson," accessed November 23, 2009, http://www.kennethsnelson.net/new_structure/structure1.htm; Eleanor Heartney, *Kenneth Snelson: Forces Made Visible* (Lenox, MA: Hard Press Editions, 2009).

threads. With inverse boundary rules, rule B-1 retrieves the boundary of these points back into lines. Rule M1 is then applied to the new lines, embedding them with tensile material property. These tensile lines hold up the knot from being disintegrated, similar to the way Tensegrity structures hold the struts with cables.

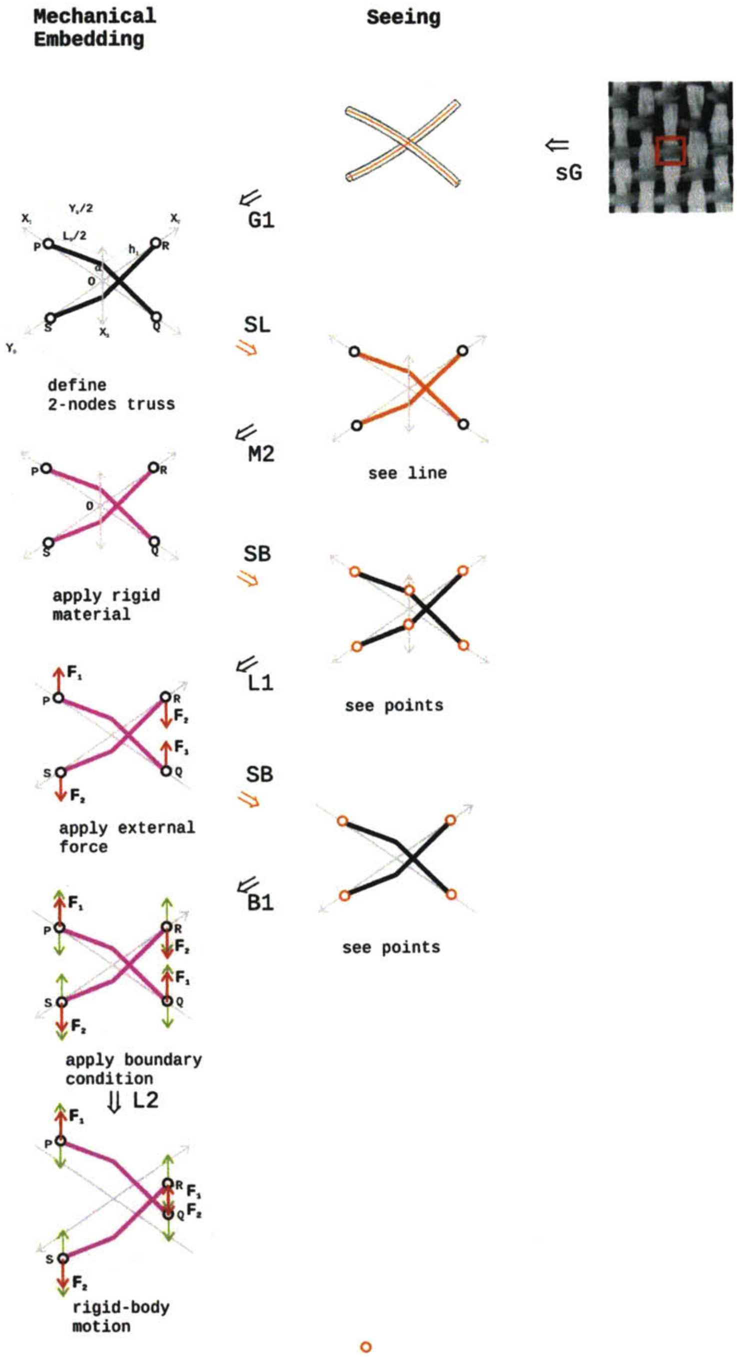


Figure 78. Abstract weaving grammar.

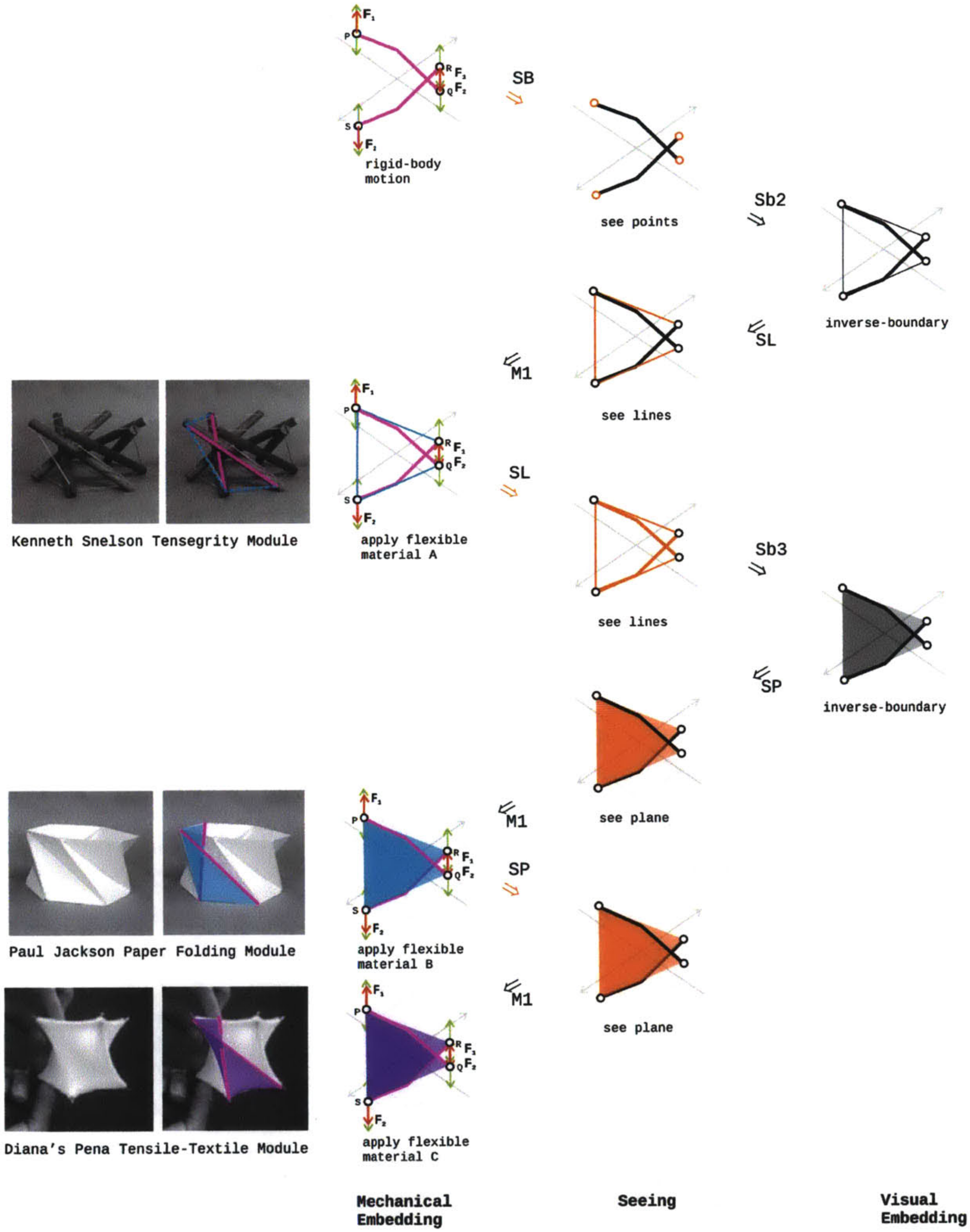


Figure 79. Abstract weaving grammar (continued.) [154]

[154] Image credit for tensegrity and paper-folding module: Fernando Sierra, The Bionics Research Group, Pontificia Bolivariana University, Colombia. From: http://www.sculptors.com/~salsbury/Synergy/. Image credit for Tensile-Textile Module: Diana Peña, Ignasi Llorens, and Ramon Sastre, "Application of the

The abstract weaving grammar can further generate more designs from this condition. From the tensile-rigid configuration, rule B highlights the tensile lines for rule SL to apply inverse-boundary rules once again onto the lines. As a result, the lines are retrieved into a plane. Rule SP then highlights this new plane, and subsequently, rule M embeds an anisotropic material property into the plane.[155] The knot then behaves like a module of folded sheet, where in this module, the threads become the folding lines.

Repeating rule M1 in this form would change the material properties once again. From the folding module, rule SP highlights the plane and then rule M1 applies a different material property onto the plane: isotropic material (e.g., glass, metal, fabrics). The threads remain rigid, yet the plane is flexible. Examples in Figure 7977 show the same folding module with different material properties, i.e., sticks and fabrics.

Thus, within the same over-and-under configuration, the knot has been transformed into a different spatial and mechanical configuration.

Case Studies

The examples in the previous section show the way a knot's mechanical reconfiguration derives different kinds of knot designs that exist. In the following case studies, I demonstrate the same strategies to reconceptualize weaving into a novel architectural component.

Study 1: Woven Brick

This case study illustrates the way a weaving material's reconfiguration translates elements of handicraft weaving into an architectural component. In this case, I used a mat-weaving surface as a basis to generate the component's design. I describe the design generation in three phases: (1) visual embedding, (2) shape materialization, (3) and shape computation.

Tensegrity Principles on Tensile Textile Constructions," *International Journal of Space Structures* 25, no. 1 (March 1, 2010): 57–68, doi:10.1260/0266-3511.25.1.57.

[155] Anisotropy is the property of being directionally dependent in a material, such as in the case of wood, which is easier to split along its grain than against it. Isotropic material has properties that behave in the same manner in all directions, such as glass or metal.

In the visual embedding phase, a weaving surface is considered as an initial condition to embed new shapes. In this initial condition, shapes on the surface are explored as a two-dimensional pattern, from which a 2-D rectangular shape is chosen (Figure 8078).

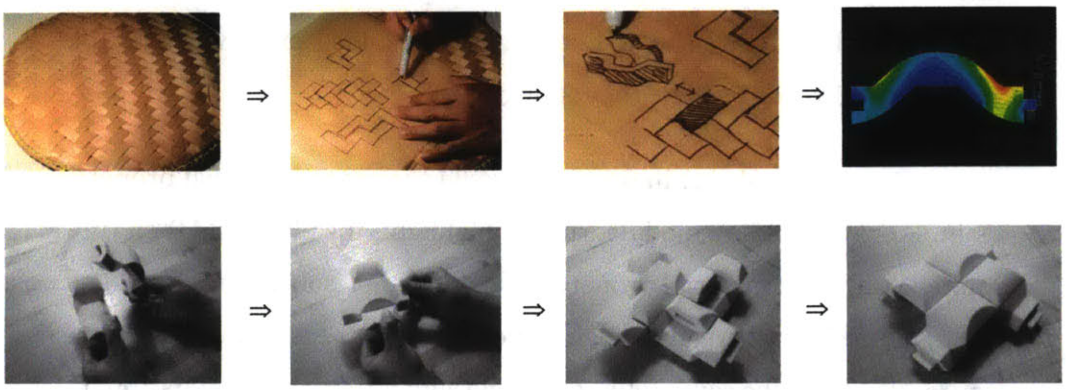


Figure 80. 2D - 3D Weave
With a woven mat as an initial design, the first step considers the mat-weave as a 2-D pattern consisting of many shapes. After a shape is defined, the material properties are embedded in the shape. In this case, the shape is assumed to be rigid instead of flexible. With the rigid shape, I then *remember* the weaving mechanism by applying the overlapping and reciprocal configuration of weaving.

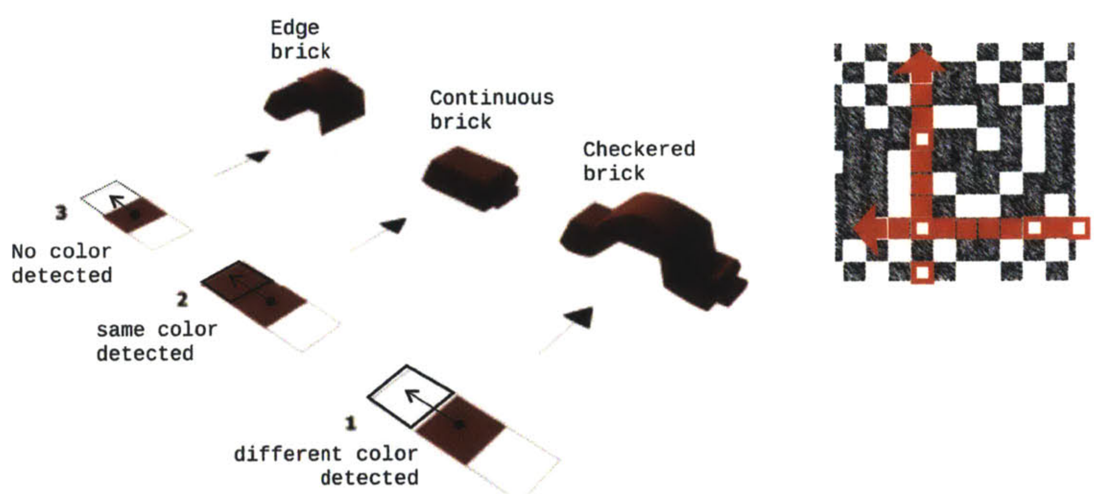
In the shape materialization phase, the chosen rectangular shape is retrieved back to its 3-D appearance—a thread with a certain thickness. In this dimension, the shape is embedded with rigid material property and optimized to withstand external loading. The optimized shape is rendered as a brick. In particular, three kinds of brick were defined to reproduce a traditional woven motif in architectural scale: (1) the "edge brick" for the "erasing" rule, (2) the "checkered brick" for the checkered motif, and (3) the "continuous bricks" for the continuous straight line (Figure 8179). The pixelated pattern in the traditional woven pattern corresponds to the surface of the brick.

In the shape computation phase, the method of assembling the brick into a point's composition is formulated into computational rules. Three rules guide the brick assembly process by focusing on two cells in the pattern (black and white):

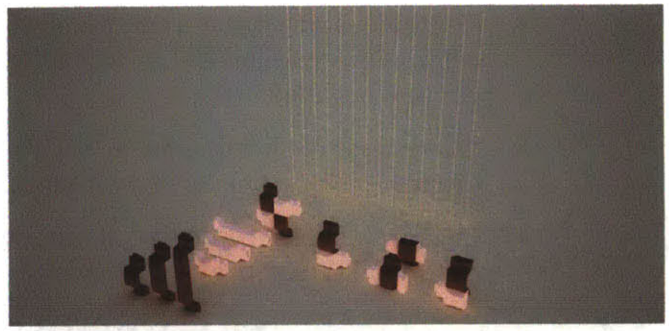
- Continuous rule forms a continuous line: IF the next cell is of the same color as the previous cell, THEN add a continuous brick to form a continuous line;
- Checkered rule forms a checkered pattern: IF the next cell has different color from the previous cell, THEN use a checkered brick;
- Edge rule stops the iteration at the edge of the surface: IF there is no cell found, THEN use an edge brick.

Each brick is connected to the other bricks via notches and tabs. Simultaneously, the bricks create a self-supported surface and a mosaic pattern that requires a minimal amount of binding component such as cement or mortar.[156,157]

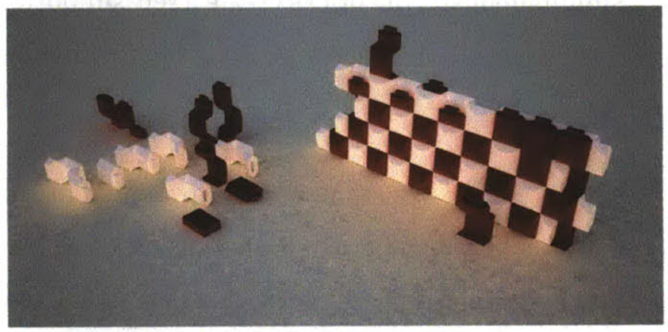
Figure 8280 shows an illustration of the brick application. As flexible material (e.g. bamboo) in traditional weaving is considered less permanent for architectural function, the brick, as an alternative embodiment of weaving principles, shows a promising weaving application in architectural scale for a long-term purpose.



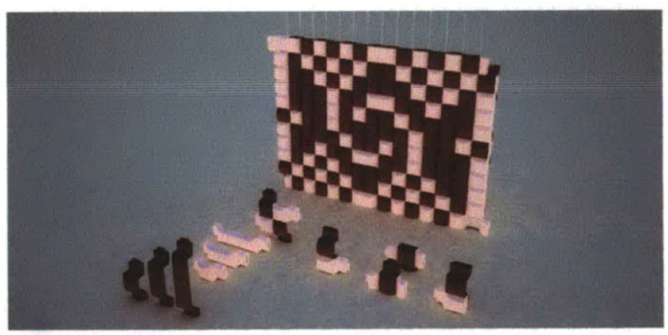
[156] Also note that in this project, the brick module has a rectilinear grid, which creates a rectilinear surface. Likewise, different brick modules, such as a diamond, circular, or triangular shape, will create different geometrical patterns.
[157] Similarly, to eliminate the need for mortar, create low-cost patterns using Meander Grammar_as in Larry Sass's and Terry Knight's "Meandering Brick." The "Meandering Brick" has integrated alignment features (i.e., two horizontal notches and one vertical notch serve as aligners) that can be easily matched and manually locked together without mortar [157].



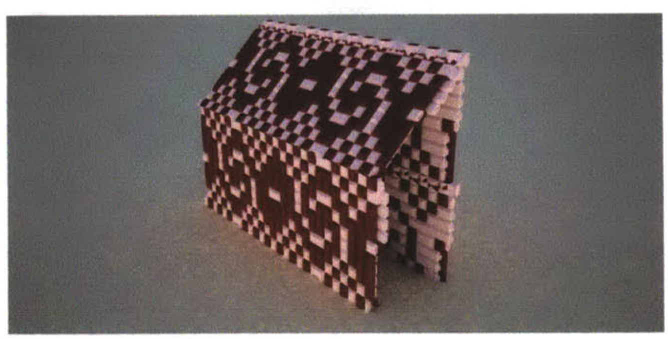
1. Projecting the Grid



2. Applying Checkered Rule



3. Applying Linear and Edge Rule



4. Continue on slated surface

Figure 81. Weaving a brick

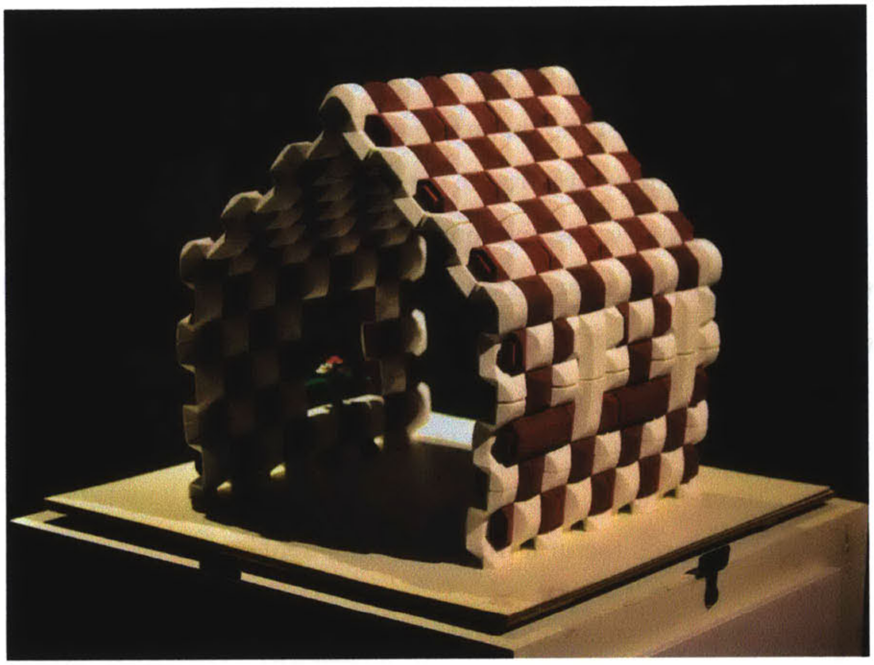


Figure 82. Woven house scaled model (top) and application illustration (bottom)

Study 2: Bead-Brick

In this case study, I investigate an alternative approach to generating a shape by considering different sources for the shape's geometry and different materials for the shape's physical properties compared to the previous case. In terms of the source for the shape's geometry, the previous case study (woven brick) shows the way a shape is embedded from a thread's surface. In this case, I show another example where a shape is embedded from the space between the interwoven threads. In terms of material, previous case studies (woven timber and woven brick) demonstrated how weaving is applied to rigid material to replace the flexible material. This case study investigates ways to incorporate both rigid and flexible materials into an architectural weaving component.

In the following, I illustrate my investigation through the phases of visual embedding, shape materialization, and shape computation ..

In the visual embedding phase, the initial condition in this case study is the shadow of a triaxial-weave basket. From this shadow pattern, a hexagon and the overlapping triangles are chosen.

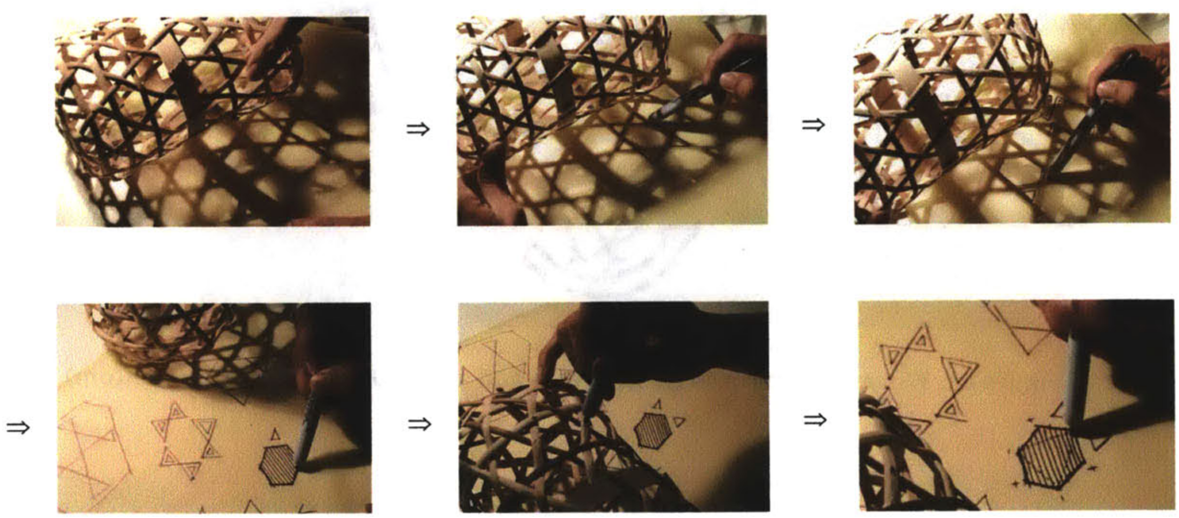


Figure 83. Visual Embedding in the Shadow patterns

In the shape materialization phase, I develop the hexagon and triangles into 3-D shapes through mechanical and visual embedding (Figure 8482). To generate rigid material, I retrieve the point as the boundary of the shapes (step 2 to 3). Using these points, I then apply force to pull the triangles away from each other (step 4 to 5). As the triangles are separated, rule B1 retrieves the inverse boundary of the triangles' points into a 3-D shape and embeds the shape into rigid material (step 6 to 7). To optimize this rigid shape, parts that are at risk of cracking (at the tip of each corner) and parts that do not have large stress distribution (center of the shape) are removed (step 13 to 15).

To generate the flexible material, I use inverse boundary rules at the same initial points at the beginning (step 10). At these points, I generate three lines that intersect in the middle of the hexagon (step 11). Into these lines, I apply flexible material property (step 12). These lines go through the 3-D shapes similarly to the way string goes through a bead in traditional beading. Based on this, the 3-D shape hereafter is referred to as a *bead* and the lines as a *string*.

In the shape computation phase, the way this bead is assembled is formulated into a transformation rule—in particular, the transformation that benefits the inherent geometrical properties of the bead.

The bead has three sides to support its adjacent beads and three sides to be supported by its neighboring beads. To connect and hold the bead together with the other beads, the strings go through the bead and compact the bead similarly to the way traditional beads are tightened and bound together with tension. The combination of compression from the sides of the bead and tension from the thread holds the shape together to withstand both axial and lateral loads from external forces.[158]

[158] According to the FEM analysis, the center of this shape does not share the same stress as the other sides; therefore, the center part is subtracted from the shape. The empty space allows the hand to maneuver the string to tighten the bead. This also helps reduce the weight of the material.

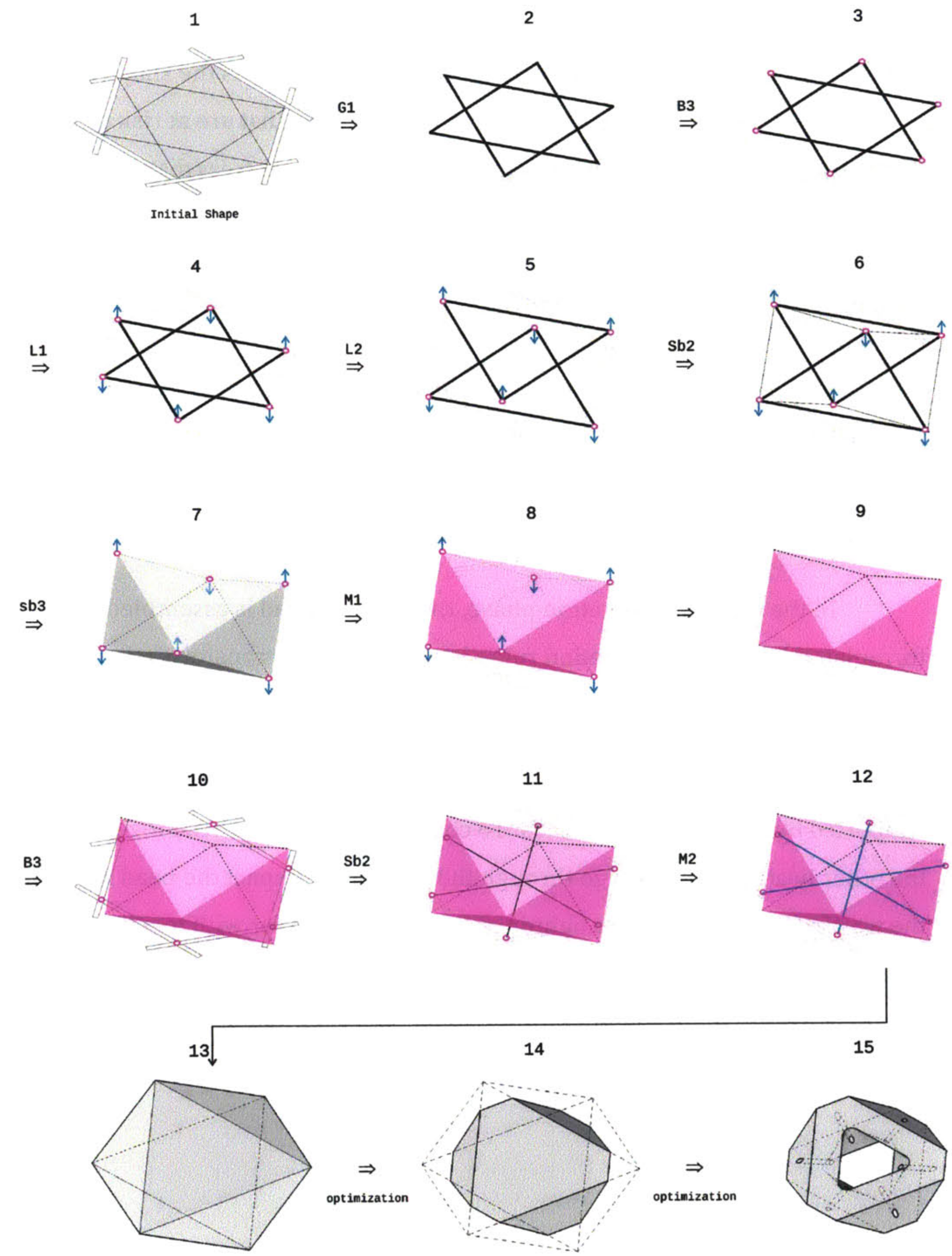


Figure 84. Bead Transformation

The bead has the order symmetry of 12 -- that is, there are 12 different ways the beads can be placed in a shape relationship. With these orders of symmetry, two beads can be arranged in various 2-D and 3-D shape relationships. In the 2-D relationship, two beads meet as shown in Figure 8583.[159] In a 3-D relationship, two beads are connected so that the two share a large surface to support each other in 3-D composition (Figure 8785). With this type of connection, the resulting shape computation generates some emergent design possibilities that could produce new shapes, such as a tetrahedron, which could later serve in a new module as an initial shape.

Figure 85. 2D shape relationships

[159] By comparison, 24 basic designs can be derived from its basic shape relationships with two beads (12 symmetry x 2 beads). To develop a basic loop of triaxial beading with three beads, we can make 36 designs (12 symmetry x 3 beads), and to develop a hexagonal beaded loop with seven beads, we can make at least 84 basic designs (12 symmetry x 7 beads).

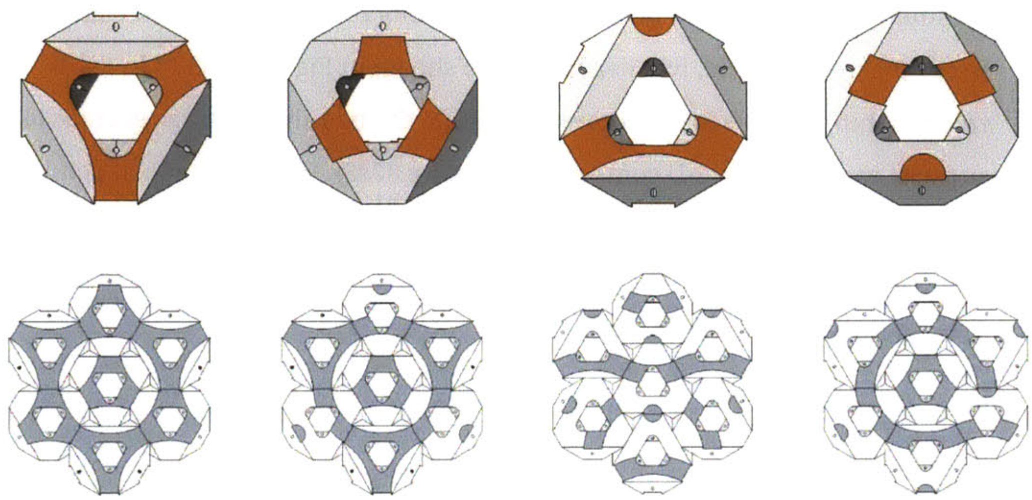


Figure 86. Bead as an initial shape and ornamental variations
Four ornamental designs at the bottom show the variation of ornaments based on the ornament's symmetry.

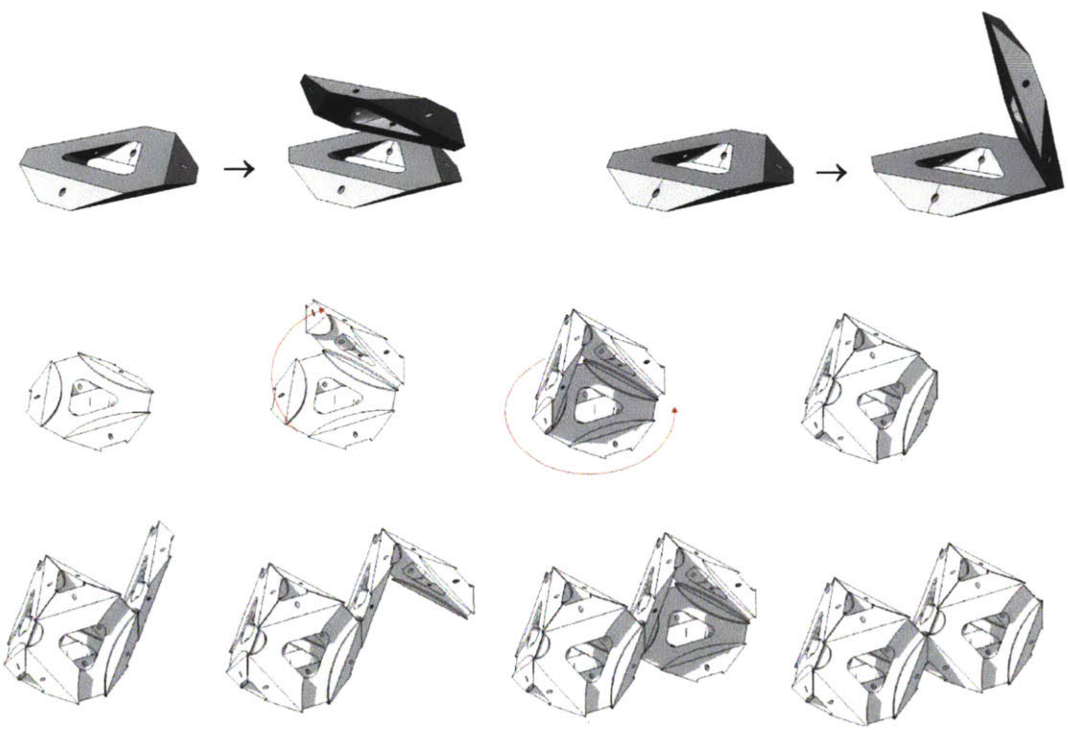


Figure 87. 3D shape relationships

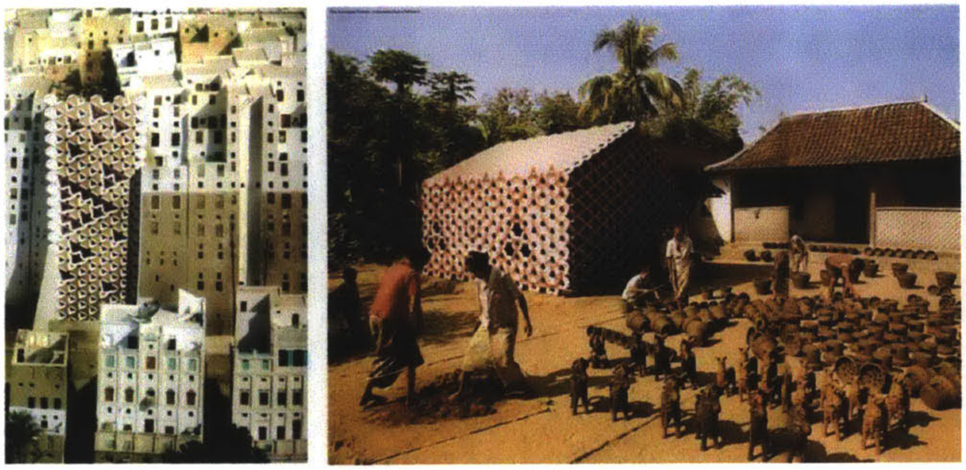


Figure 88. Illustration of architectural application

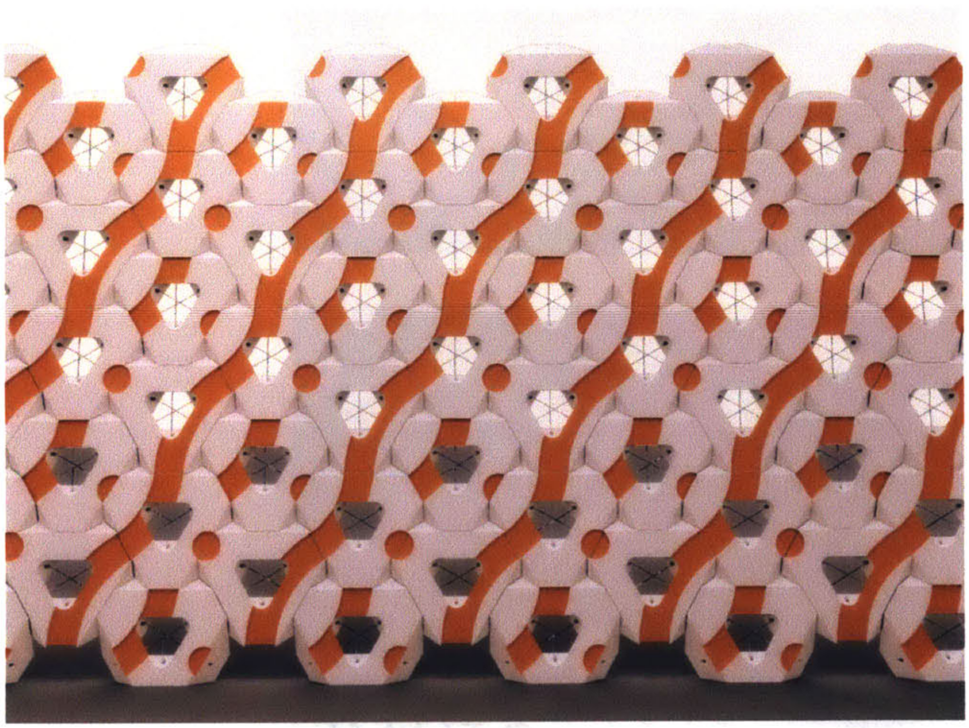


Figure 89. 2D Composition

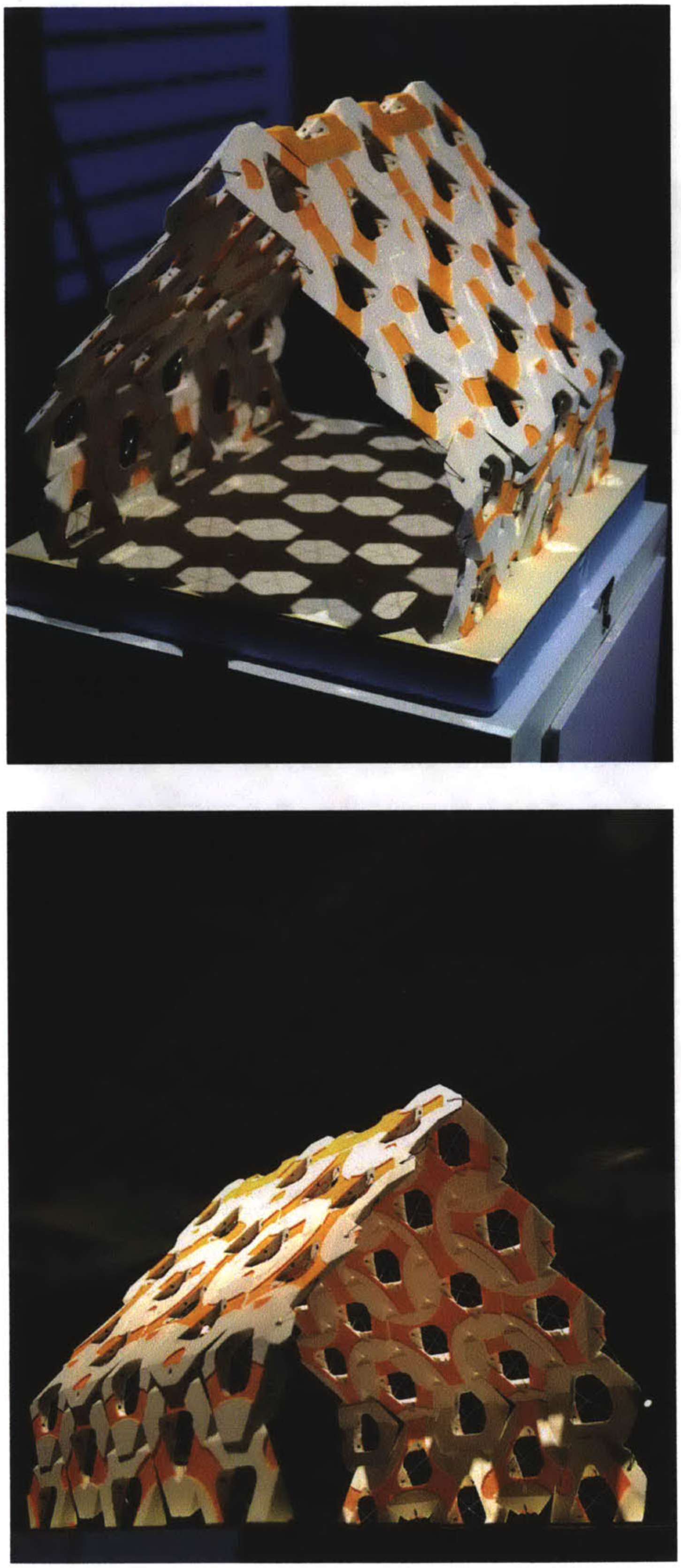


Figure 90. A Beaded House (Scaled Model)

3.4 Discussion

In this chapter, I have formulated a series of computational design methods to reinvent weaving in architectural design using both basic weaving grammar and abstract weaving grammar.

Basic weaving grammar provides a set of rules to explicitly express weaving design intentions, to generate designs from such intentions, and to evaluate the weaving condition from the generated designs. Abstract weaving grammar provides a set of rules to reconfigure the mechanics of weaving in a different way, through which a new kind of weaving design can emerge.

In the following, I summarize the way that traditional and computational methods are hybridized within the grammar, and the way that the grammar allows an expansion of the language of weaving design to contextualize computational weaving across cultures.

Traditional Computation in the Computational Tradition

This study shows that in developing the grammars, informal knowledge that is represented by mental shape and physical shape from traditional weaving is equally as important as formal theories from computational design and computational mechanics. The weaver's sensorial experience was not used merely as a metaphor but more as a tangible model that can be incorporated within the formal theories.

When developing the basic weaving grammar, I incorporated the polygon from the weaver's visual perception in formulating a set of rules for weaving intention and weaving action. Furthermore, the grammar also takes into account the knot counting process from the way the weaver visually evaluates the woven/nonwoven condition of traditional weaving. As a result, the revived mental shapes in the grammar provide an essential visual assistance to generate the weaving design in a similar fashion the mental shape may help the weaver to visually engage with the weave.

In developing the abstract weaving grammar, I have incorporated findings from the weaver's haptic experiences into a set of rules for the mechanical embedding process. The interpretation of the weaver's haptic events in sensing the weave helped me to define strategies to perceive and design the weave computationally, particularly with regard to the way in which external forces and material properties are embedded into the knot.

The Expanding Weaving Language

Several design exercises from the grammars have allowed me to analyze existing architectural weaving designs as well as synthesize a new kind of weaving for architectural design.

In exercising the basic weaving grammar, the generated designs have helped me to revisit several interwoven designs from the past, such as the reciprocal frame system. By encapsulating the existing designs as part of the computational weaving design language, I was able to reinvent the designs algorithmically for different contexts, forms, and materials.

In computing the abstract weaving grammar, the design iteration enabled me to extend my horizons of weaving design language across crafts such as paper folding and tensegrity. With this new horizon, I was able to invent new types of weaving that incorporate methods from different craft disciplines, such as beading and masonry.

Grammar Assimilation across Cultures

The field study shows that through basic weaving grammar, weaving principles that appeared to be exclusive to a certain profession are transferable across disciplines.

I have demonstrated grammar application across media with engravers and carpenters in Toraja. With paper and pens as visual media, the engravers easily comprehended the weaving grammar. With wooden beams as physical media, the grammar helped the carpenter to build a woven-timber installation within one day. Moreover, grammar comprehension allowed people across age groups, from craftsmen in Toraja to students from the fifth to ninth grades in Cambridge, to learn and generate rules from computational weaving.

4 CONCLUSIONS

4.1 Summary

In this dissertation, I have outlined my strategies for reinventing architectural weaving through *in situ* observation and computational design formulation.

Via a computational lens, traditional weaving that seems deceptively simple appears to be more complex, collaged with mental shapes that are tacitly embedded in the weaver's perceptions. Analysis of the weaver's mental shapes highlights some aspects of weaving that are not bound by the weave's physicality. This analysis allows these aspects of weaving to be used for other applications across scale and disciplines.

With explicit representation, the mental shapes are better able to be incorporated with computational design methods to develop a Weaving Grammar. The set of rules in the Weaving Grammar is not only able to analyze existing cases, but also to synthesize new weaving designs for architectural use. With the increase in new designs, the language of architectural weaving is expanded.

EthnoComputation as a Fieldwork Companion

I titled this thesis 'EthnoComputation' to underline the pivotal role of the human being in sensing and computing. EthnoComputation helped me, the observer, to interpret weaver-weave interaction by looking at the shapes that are exchanged within the weaver's inner-outer environment during his weaving process.

In brief, EthnoComputation helped me to learn from a craftsperson through the following sequence:

First, I defined an interface between the weaver and the weave. In this interface, shapes from the weaver's inner environment – mental shapes – interact with shapes from his outer environment – physical shapes. In the case of weaving, the interface is the weaver's seeing and touching activities. In the case of bamboo fabrications, the interface is the weaver's bamboo cutting activities.

Second, I interpreted the weaver's mental shapes as an explicit computational iteration. The iteration is discretized based on changes in the weaver's sensory attention – e.g., gaze shifting in the weaver's vision. When the craftsperson is not present, the iteration is discretized based on the craft object's variations on the site – e.g., differences in the shape of the bamboo on the site.

Third, I examined the reasons underlying the use of mental shapes in the weaver's action. The examination is subject to several aspects in the weave (e.g., form and material) and to theories that pertain to the weaver's sensorial experience (e.g., Gibson's Perceptual System). The mental shapes in each step were analyzed individually to elucidate each one's relationship with the physical shape. To make it possible to analyze several mental shapes simultaneously, the shapes were superimposed in layers so as to reveal the most repeated thread's position within several steps.

The Roundtable in Mind

From EthnoComputation study, shapes from the weaver's sensorial experience are incorporated in the process of developing the Weaving Grammars. A set of rules provided in the grammars allows an architect to negotiate design opportunities and consequences during the early design conceptualization that could anticipate potential issues between shapes and conflicting descriptions.

A design contains shapes and an intention underlying design contains a certain description. In architectural design, a shape can embody different descriptions and a certain description can fit different shapes. The two can coexist or be independent from one another. This, however, is not always the case between design and intention in practice. Sometimes the relationship between the two is tightly bonded in that the design *becomes* the intention. In this tight bond, shapes in the design are fixed by the intention's descriptions. For instance, a project brief may say, 'a design is supposed to be effective'. If many precedents show that vertical shapes are efficient, then the vertical design could become *the* intention, regardless of other possible 'efficient' shapes. Here, shapes become fixated by description, and too rigid for further manipulation (see 'design fixation' in chapter 1).

In the weaving grammars, this research minimized such fixation by untying shape from weaving's description. In the grammar, "weaving" is conceived as an umbrella term that describes an over-and-under shape-relationship that is composed into a cyclical configuration. Any designs that fit this description can be encapsulated into the language of weaving, regardless of scale, shape and material.

This conception allows a designer to synthesize many shapes for weaving design while at the same time providing guidelines to ensure that the synthesized design fits with the weaving description. To fit the description, rules in Basic Weaving Grammars work in tandem: the additive rules generate various over-and-under design compositions, while the erasing rules confirm that the designs satisfy the cyclical configurations.

4.2 The Limits and the Prospects

In this section, the limitations of this research and suggestions to leverage these limitations for future studies are discussed.

Augmented-Me: The Future of EthnoComputation

The field study in this research was conducted by simulating the way I learned from a weaver in a tacit environment. The data from the weaver-weave interaction was interpreted using my own perceptual apparatus. As a result, the data sampling from this interaction has limited precision.

Nevertheless, the process of the weaver-weave interaction was interpreted through the EthnoComputation framework that organizes how to represent the weaver's sensorial experience explicitly. This framework could lay the foundation for future use of cutting-edge technology in capturing more accurate data from observation. For instance, the EthnoComputation framework could help by channeling the data gathered by sensory devices, such as eye-tracking devices, body-motion sensors, and thermal-imaging sensors, into a meaningful representation for design study. Furthermore, the EthnoComputation framework could help organize other types of data that are enabled by this technology. For example, the framework could to used to investigate the shape-and-time relationship between a shape that the weaver sees on the thread and the exact moment he starts applying muscular force to move the thread. To capture the data, the weaver's gaze at the thread could be captured by an eye-tracking device, and the weaver's muscular force could be detected by a thermal-imaging sensor and body-motion sensor. (However, to preserve the weaver's natural activities, the use of sensors should intrude as little as possible.)

For better EthnoComputation studies, it is imperative to view the sensorial technology as an extension of the observer's sensorial apparatus, instead of as a replacement for the observer's intuition in interpreting the sensorial data. The value of EthnoComputation rests upon non-deterministic data interpretation. In terms of design, different data interpretation would lead to new design reinvention strategies, and in terms of research, different interpretation methods would enrich the repertoire of computational studies on learning design in tacit environments.

Digital Shape: On Weaving and Automation

The building workshop in Toraja focused on examining the cycle of design analysis – design synthesis – design construction. It has yet to examine the subsequent cycle of building construction – building occupancy – building demolition/reuse. Thus, although the grammar of the architectural component was easy for local craftspeople to learn, fabricate and assemble, there are other architectural aspects of the component that need to be inspected. To meet desired structural requirements and environmental constraints, the new designs (e.g., woven-timber, woven-brick and bead-brick) would need more rigorous scrutiny.

This indicates the need for effective methods, such as digital simulation, to examine structural or other requirements. Here, the algorithmic form of the Weaving Grammar comes into play. As an algorithm, the rules of the grammar can be encoded directly into a computer program, through which the digital grammar can instantly generate, evaluate and optimize the generated weaving designs.[161]

Having said that, the pair of human and computer in computing the Weaving Grammar should be symbiotic, as is the pair of aiming-shooting an arrow and the flight of an arrow in archery. The aiming and shooting depend on the archer's mind and sensory-motor skill. The arrow's flight is entrusted to the laws of nature.[162] The former process is slower, yet crucial and mandatory for the latter. The latter process is faster and self-regulating, yet computable by the former process.

This study acknowledges the significance of human sensing and computation as the predecessor to digital computation. While digital computation offers high-speed and precise processing, the benefit of human computation lies in the absence of speed and a determinate answer. In human computation, a slower process leads to more designs being contemplated, and indeterminate answers may lead to more design solutions.[163]

In EthnoComputation, I have iterated the slow computation process wherein a mental shape that the weaver perceived for less than a second was interpreted over a several-month period during this thesis process into many alternative shapes. In the Weaving Grammars, I demonstrated an indeterminate computation in which different ways of looking at the shape generates many weaving designs.

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[161] For more example on how the grammar is translated into a script language, see Rizal Muslimin, "Interweaving Grammar: Reconfiguring Vernacular Structure Through Parametric Shape Grammar," *International Journal of Architectural Computing* 8, no. 2 (September 1, 2010): 93–110, doi:10.1260/1478-0771.8.2.93.

[162] The interaction between the arrow's outer environment, e.g. air speed, wind-direction, gravity, and inner environment e.g., mass, materials, force and velocity.

[163] See more about 'Slow Theories' and the benefit of Slow Computation in Terry Knight, "Slow Computing: Teaching Generative Design with Shape Grammars," in *Computational Design Methods and Technologies: Applications in CAD, CAM and CAE Education*, ed. Ning Gu and Xiangyu Wang (IGI Global, 2012), http://www.igi-global.com/chapter/slow-computing-teaching-generative-design/62940., p.35

4.3 Borderless Weaving

It would be misleading to claim that the EthnoComputation study establishes how the weaver thinks about weaving, or that the rules in the Weaving Grammars demonstrate how past designers reinvented weaving. There are weaving designs produced without the Weaving Grammars. There are designers who might develop similar weaving design-rules without observing the traditional weaver.

The coexistence of traditional weaving and computational weaving in this study is not about nostalgic preservation of traditional craft. Nor is it about cultural justification of a computational process. Here, their coexistence is part of a strategy of systematizing design resources (in traditional craft) and design conceptualization (in architectural design). In this system, inspirations and ideas become computable, regenerative and renewable. EthnoComputation and Weaving Grammar have linked traditional weaving and architectural weaving with regard to the way in which weaving principles can be applied across disciplines, hence blurring the boundary between crafts and architecture.

Within this borderless setting, the strong affiliation of weaving and architecture in their origins was revisited and revitalized in this thesis.

4.4 Epilogue

Toward the end of work on this dissertation, several headlines demonstrated the emerging recognition of digital manufacturing as a national asset. In Zurich, the architecture and digital fabrication lab at ETH, led by Matthias Kohler, received a substantial grant from the Swiss government to advance architectural building methods through research in robotics (about US$14.7 million as part of the National Centre of Competence in Research 2014-2017 programs).[165] In June 2014, in Washington, D.C., Maker Faire, an annual event for the digital fabricator community, was held for the first time on the White House lawn. The exhibition revealed the democratization of digital technology and the emerging Do-It-Yourself (DIY) mentality within American society.

The headlines from Zurich and Washington, D.C., suggest that rethinking the production system for building architecture is becoming equally as important as valuing the built architecture as a product.

Government support for digital manufacturing, either by the Swiss or the U.S. governments, indicates a political effort to assimilate manufacturing technology as part of a nation's culture. For Switzerland, this strategy is pragmatic and rational. The high hourly wage in their manufacturing industry (i.e., the second-highest in the world at $34.29/hr.)[166] justifies their research budget to increase the capacity of their robotic technology to minimize labor costs. For the U.S. government, hosting the Maker Faire event is an endorsement that supports the "American Manufacturing Renaissance".[167] Disney's popular mantra in Maker Faire that "if you can dream it, you can make it", is well aligned with the American motto that "if you work hard, you can get ahead."

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[165] As part of the new National Centres of Competence in Research (NCCR). Source available from: http://www.sbfi.admin.ch/themen/01367/01677/index.html?lang=en

[166] Based on Global Wage Report 2012/13: Wages and equitable growth: (International comparison of hourly direct pay for time worked in manufacturing, 2010) , published by the International Labour Organization (ILO). Available from: http://www.ilo.org/global/publications/lang--en/index.htm

[167] Becky Fried and Becky Wetstone, "President Obama at the White House Maker Faire: 'Today's D.I.Y. Is Tomorrow's "Made in America"' | The White House," June 18, 2014, http://www.whitehouse.gov/blog/2014/06/18/president-obama-white-house-maker-faire-today-s-diy-tomorrow-s-made-america.

The national context of robotic technology and 3D printing justifies efforts at technological advancement. This justification sheds light on a larger implication of reinventing traditional crafts via computational methods. Compared to Switzerland and the U.S., the context of this study is more modest, yet nevertheless unique.

In terms of labor cost, developing countries such as Indonesia have a low hourly wage (around US$75/month. to US$200/month.).[170] Additionally, the country has a large labor force (about 116,500,000). Thus, it presents an opposite situation to that of Switzerland, which has a much smaller labor force.

In terms of knowledge assimilation, the nature of crafting knowledge distribution is tacit. In contrast, one important source of the Maker Faire's success is that the knowledge is explicit and accessible. This explicit knowledge, along with the affordability of buying the components, has helped to accelerate the democratization of digital technology in the U.S.

However, in terms of craftsmanship, the Torajan community has many crafting disciplines, each of which expresses diverse techniques and designs. The craftspeople are supported by the abundance of local materials. In this fertile environment, crafting is pervasive and diverse, manifesting itself in the production of accessories, handicrafts, clothes musical instruments and buildings themselves.

Correspondingly, crafting activities in Toraja, as local context, justified my computational design strategy. In adapting this strong crafting culture, the issues of labor and knowledge distribution were contextualized two strategies.

First, the assembly techniques for the new designs were tailored for human hands rather than robotic arms. To weave the timber beams, one needs to fit the notches of one beam with the tabs from the neighboring beams. To bead

[170] Based on the Ministry of Manpower and Transmigration of the Republic of Indonesia report on the 2014 Regional Minimum Wage (UMR) . Source available from: http://infokerjadepnaker.blogspot.com/2013/11/Daftar-Gaji-Terbaru-UMR-UMK-Regional-Kota-Seluruh-Indonesia.html

the bricks, one needs to insert the strands through a small hole in a brick, weave the threads inside the brick's hole, and compact the bricks by pulling the strands and packing the bricks together. These maneuvers are relatively complex to be executed by robots.

Second, the visual representation of the Weaving Grammar allows the craftsman to learn the rules tacitly. Furthermore, the grammar is not tightly bonded with a certain medium. The media can be visual or physical. As a result, the grammar can be computed across crafts disciplines in Toraja, such as in drawing by the engravers and in assembling the timber by the carpenter. By having the grammar used in different crafts, the nature of the design in each craft can enrich the design language and the versatility of the grammar.

The above strategy shows that the absence of computer-aided manufacturing at the traditional site does not mean a computational fabrication cannot be performed. The case studies show that without computers, the craftsman can nonetheless employ computational thinking.

Thus, introducing a machine to replace the labor force in traditional crafts may not be culturally sustainable. Teaching computational design methods to craftspeople so that they can develop their own rules and designs may be more empowering. The Indonesian crafting renaissance has yet to come. But if it is developing, it is unlikely to resemble what was showcased at the Maker Faire festival. The renaissance may be quiet and tacit, yet perceptible and computable.

BIBLIOGRAPHY

Adams, Kathleen M. *Art as Politics: Re-Crafting Identities, Tourism, and Power in Tana Toraja, Indonesia.* Honolulu: University of Hawaii Press, 2006.

Albers, Anni. *On Weaving.* Wesleyan University Press, 1965.

Alexander, J. W. "Topological Invariants of Knots and Links." *Transactions of the American Mathematical Society* 30, no. 2 (1928): 275–306. doi:10.1090/S0002-9947-1928-1501429-1.

American, Mathematical Society. *Applications of Knot Theory: American Mathematical Society, Short Course, January 4-5, 2008, San Diego, California.* Providence, R.I: American Mathematical Society, 2009.

Ascher, Marcia. *Mathematics of the Incas: Code of the Quipu.* Dover Publications, 1997.

Ateshian, Gerard A. "Artificial Cartilage: Weaving in Three Dimensions." *Nat Mater* 6, no. 2 (February 2007): 89–90. doi:10.1038/nmat1830.

Barker, Henry. *Egyptian Gods & Goddesses.* Grosset & Dunlap, 1999.

Barlow, Alfred. *The History and Principles of Weaving, by Hand and by Power.* London: Low, Marston, Searle, & Rivington, 1878.

Bathe, Klaus-Jürgen. *Finite Element Procedures.* Englewood Cliffs, N.J: Prentice Hall, 1996.

Bell, T. F. *Jacquard Weaving and Designing.* Longmans, Green, 1895.

Boas, Franz. *Primitive Art.* 1st Dover Edition. Dover Publications, 1955.

Bucalem, Miguel Luiz, and Klaus-Jurgen Bathe. *The Mechanics of Solids and Structures - Hierarchical Modeling and the Finite Element Solution.* 2011 edition. Berlin; New York: Springer, 2011.

Deleuze, Gilles. *A Thousand Plateaus: Capitalism and Schizophrenia.* Minneapolis: University of Minnesota Press, 1987.

———. *Bergsonism.* New York: Zone Books, 1988.

Dietz, Ada K. *Algebraic Expressions in Handwoven Textiles.* Louisville, Kentucky: The Little Loomhouse, 1949.

Dunkelberg, Klaus. *IL 31, Bambus. IL 31, Bamboo. Bambus Als Baustoff. Bauen Mit Pflanzlichen Stäben.* Krämer, Stuttgart, 2000.

Eglash, Ron. *African Fractals: Modern Computing and Indigenous Design.* 3rd edition. New Brunswick, N.J: Rutgers University Press, 1999.

———. "Culturally-Situated Design Tools." *Culturally Situated Design Tools: Teaching Math and Computing through Culture.* Accessed May 16, 2014. http://csdt.rpi.edu/.

Eglash, Ron, Audrey Bennett, Casey O'donnell, Sybillyn Jennings, and Margaret Cintorino. "Culturally Situated Design Tools: Ethnocomputing from Field Site to Classroom." *American Anthropologist* 108, no. 2 (June 1, 2006): 347–62. doi:10.1525/aa.2006.108.2.347.

Elkins, James. *What Painting Is.* 1 edition. Routledge, 2004.

Erkki Sutinen, Mikko Vesisenaho. "Ethnocomputing in Tanzania: Design and Analysis of a Contextualized ICT Course." *Research and Practice in Technology Enhanced Learning* 1 (2006): 239–67. doi:10.1142/S1793206806000238.

Essinger, James. *Jacquard's Web: How a Hand-Loom Led to the Birth of the Information Age.* Oxford: Oxford University Press, 2004.

Evans, Miriama. *The Art of Māori Weaving : The Eternal Thread.* Wellington N.Z.: Huia Publishers, 2005.

Fried, Becky, and Becky Wetstone. "President Obama at the White House Maker Faire: 'Today's D.I.Y. Is Tomorrow's "Made in America"' | The White House," June 18, 2014. http://www.whitehouse.gov/blog/2014/06/18/president-obama-white-house-maker-faire-today-s-diy-tomorrow-s-made-america.

Geertz, Clifford. *Works and Lives: The Anthropologist as Author.* 1 edition. Stanford, Calif.: Stanford University Press, 1989.

Gerdes, P. "Fivefold Symmetry and (basket) Weaving in Various Cultures." *Fivefold Symmetry*, 1992, 245.

Gibson, James Jerome. *The Ecological Approach to Visual Perception.* Routledge, 1986.

———. *The Senses Considered as Perceptual Systems.* Boston: Houghton Mifflin, 1966.

Gillow, John, and Bryan Sentance. *World Textiles: A Visual Guide to Traditional Techniques.* Thames & Hudson, 2005.

Goldstein, E. Bruce. "The Ecology of J. J. Gibson's Perception." *Leonardo* 14, no. 3 (Summer 1981): 191–95.

Greenfield, Patricia Marks. *Weaving Generations Together: Evolving Creativity in the Maya of Chiapas.* Illustrated edition. School of American Research Press, 2004.

Hamedi, Mahiar, Robert Forchheimer, and Olle Inganas. "Towards Woven Logic from Organic Electronic Fibres." *Nat Mater* 6, no. 5 (May 2007): 357–62. doi:10.1038/nmat1884.

Heartney, Eleanor. *Kenneth Snelson: Forces Made Visible.* Lenox, MA: Hard Press Editions, 2009.

Hockings, Paul. *Principles of Visual Anthropology.* 3 edition. Berlin: De Gruyter, 2003.

Ingold, Tim. *Bringing Things Back to Life: Creative Entanglements in a World of Materials.* Working Paper. Realities / Morgan Centre, University of Manchester, July 20, 2010. http://www.manchester.ac.uk/realities/publications/workingpapers/.

———. *Making: Anthropology, Archaeology, Art and Architecture.* Routledge, 2013.

———. "Of Blocks and Knots: Architecture as Weaving." Accessed May 17, 2014. http://www.architectural-review.com/comment-and-opinion/of-blocks-and-knots-architecture-as-weaving/8653693.article.

Jansson, David G., and Steven M. Smith. "Design Fixation." *Design Studies* 12, no. 1 (January 1991): 3–11. doi:10.1016/0142-694X(91)90003-F.

Kawabata, S., Mari Inoue, and Masako Niwa. "Non-Linear Theory of the Biaxial Deformation of a Triaxial-Weave Fabric." *Journal of the Textile Institute* 83, no. 1 (1992): 104–19. doi:10.1080/00405009208631180.

Kawabata, S., Masako Niwa, and H. Kawai. "3—the Finite-Deformation Theory of Plain-Weave Fabrics Part I: The Biaxial-Deformation Theory." *Journal of the Textile Institute* 64, no. 1 (1973): 21–46. doi:10.1080/00405007308630416.

"Kenneth Snelson." Accessed November 23, 2009. http://www.kennethsnelson.net/new_structure/structure1.htm.

Kent, Kate P. "West African Decorative Weaving." *African Arts* 6, no. 1 (October 1, 1972): 22–88. doi:10.2307/3334637.

Kis-Jovak, Jowa Imre. *Banua Toraja: Changing Patterns in Architecture and Symbolism Among the Sa'dan Toraja, Sulawesi, Indonesia.* Amsterdam: Royal Tropical Institute, 1988.

Knight, T W. "Transformations of the Meander Motif on Greek Geometric Pottery," Design Computing, no. 1 (1986): 29–67.

Knight, T. W. "Constructive Symmetry." *Environment and Planning B: Planning and Design* 22, no. 4 (1995): 419–50. doi:10.1068/b220419.

Knight, T. Weissman. "Languages of Designs: From Known to New." *Environment and Planning B: Planning and Design* 8, no. 2 (1981): 213–38. doi:10.1068/b080213.

Knight, Terry. "Computing with Ambiguity." *Environment and Planning B: Planning and Design* 30, no. 2 (2003): 165–80. doi:10.1068/b12915.

———. "Computing with Emergence." *Environment and Planning B: Planning and Design* 30, no. 1 (2003): 125–55. doi:10.1068/b12914.

———. "Slow Computing: Teaching Generative Design with Shape Grammars." In *Computational Design Methods and Technologies: Applications in CAD, CAM and CAE Education,* edited by Ning Gu and Xiangyu Wang. IGI Global, 2012. http://www.igi-global.com/chapter/slow-computing-teaching-generative-design/62940.

Knight, Terry, and George Stiny. "Classical and Non-Classical Computation." *Arq: Architectural Research Quarterly* 5, no. 04 (2001): 355–72. doi:10.1017/S1359135502001410.

———. "Making Grammar: From Computing with Shapes to Computing with Things." In *Computational Making*. London, 2014.

Kraus-Boelte, Maria, and John Kraus. *The Kindergarten Guide: The Gifts.-V.8. the Occupations*. Nabu Press, 2010.

Larsen, Olga Popovic. *Reciprocal Frame Architecture*. 1st ed. Architectural Press, 2008.

Latour, Bruno. "Gaston, A Little Known Successor of Daedalus." translated by Charis Cussins, n.d.

———. """Where Are the Missing Masses? The Sociology of a Few Mundane Artifacts."""" In *Shaping Technology / Building Society: Studies in Sociotechnical Change*, by Wiebe E. Bijker and John Law. Cambridge, Mass.: The MIT Press, 1994.

Lewis, Frank A., and Robert Bolton. *Form, Matter, and Mixture in Aristotle*. Oxford, UK ; Malden, MA: Wiley-Blackwell, 1997.

Liu Suyi. "Fabric Weave Design Based on Cellular Automata Theory," May 15, 2009, 145–47. doi:10.1109/IUCE.2009.88.

MacDougall, David. *The Corporeal Image: Film, Ethnography, and the Senses*. Princeton, N.J: Princeton University Press, 2005.

Macrae, Norman. *John Von Neumann: The Scientific Genius Who Pioneered the Modern Computer, Game Theory, Nuclear Deterrence, and Much More*. AMS Bookstore, 2000.

Marmodoro, Anna. "Aristotle's Hylomorphism without Reconditioning." Accessed May 17, 2014. https://www.academia.edu/4195031/Aristotles_hylomorphism_without_reconditioning.

Marr, David, Shimon Ullman, and Tomaso A. Poggio. *Vision: A Computational Investigation into the Human Representation and Processing of Visual Information*. MIT Press, 2010.

Matti, Tedre. "Ethnocomputing: A Multicultural View on Computer Science." M.Sc Thesis, University of Joensuu, 2002.

Moutos, Franklin T., Lisa E. Freed, and Farshid Guilak. "A Biomimetic Three-Dimensional Woven Composite Scaffold for Functional Tissue Engineering of Cartilage." *Nat Mater* 6, no. 2 (February 2007): 162–67. doi:10.1038/nmat1822.

Murasugi, K. "Knot Theory in Molecular Biology." *Knot Theory & Its Applications*, 2008, 267–83.

Muslimin, Rizal. "Decoding Passura' – Representing the Indigenous Visual Messages Underlying Traditional Icons with Descriptive Grammar." In *Open Systems*, 781–90. Singapore: Southeast University Press Pub. Date :2007-10-01, 2013.

———. "Gestalt Grammar in Weaving Design: Leveraging Visual Affordance in Analysing and Synthesizing Weaving Design Based on the Laws of Prägnanz and Shape Grammar (poster)." Texas, USA, 2012.

———. "Interweaving Grammar: Reconfiguring Vernacular Structure Through Parametric Shape Grammar." *International Journal of Architectural Computing* 8, no. 2 (September 1, 2010): 93–110. doi:10.1260/1478-0771.8.2.93.

———. "Learning from Weaving for Digital Fabrication in Architecture." *Leonardo* 43, no. 4 (July 16, 2010): 340–49. doi:10.1162/LEON_a_00007.

———. "One-Piece Weaving: Reconfiguring Folding and Knotting Algorithm in Computational Design," 9–18. Newcastle, Australia, 2011.

———. "Recursive Embedding of Gestalt Laws and Shape Grammar in the Weaving Design Process," 1:443–49. Prague, Czech Republic, 2012.

O'Reilly, Karen. *Key Concepts in Ethnography*. SAGE Publications Ltd, 2014.

Otto, Frei. *IL-37 Ancient Architects*. Universität Stuttgart, 1994.

Otto, Berthold Burkhardt, Jugen Hennicke Frei. *IL 10 - Grid Shells*. Institute for Lightweight Structures, University Stuttgart, n.d.

Peña, Diana, Ignasi Llorens, and Ramon Sastre. "Application of the Tensegrity Principles on Tensile Textile Constructions." *International Journal of Space Structures* 25, no. 1 (March 1, 2010): 57–68. doi:10.1260/0266-3511.25.1.57.

Pink, Sarah. *Doing Sensory Ethnography*. SAGE Publications Ltd, 2012.

———. *Doing Visual Ethnography*. Second Edition edition. SAGE Publications Ltd, 2012.

———. *Doing Visual Ethnography*. Third Edition edition. SAGE Publications Ltd, 2013.

Polanyi, Michael. *Knowing and Being: Essays by Michael Polanyi*. First Edition edition. Chicago: University Of Chicago Press, 1969.

Prechtel, Martin, and Robert S. Carlsen. "Weaving and Cosmos Amongst the Tzutujil Maya of Guatemala." *RES: Anthropology and Aesthetics*, no. 15 (April 1, 1988): 122–32.

Purcell, A. Terry, and John S. Gero. "Design and Other Types of Fixation." *Design Studies*, Special Issue: Design Cognition and Computation, 17, no. 4 (October 1996): 363–83. doi:10.1016/S0142-694X(96)00023-3.

Salvadori, Mario. *The Art of Construction: Projects and Principles for Beginning Engineers and Architects*. 3rd ed. Chicago: Chicago Review Press, 1990.

Semper, Gottfried. *The Four Elements of Architecture and Other Writings.* Reissue. Cambridge University Press, 1851.

Sentance, Bryan. *Basketry: A World Guide to Traditional Techniques.* Thames & Hudson, 2007.

Shields, Christopher. "Aristotle." In *The Stanford Encyclopedia of Philosophy,* edited by Edward N. Zalta, Spring 2014., 2014. http://plato.stanford.edu/archives/spr2014/entries/aristotle/.

Simon, Herbert A. *The Sciences of the Artificial - 3rd Edition.* 3rd ed. The MIT Press, 1996.

"SmartBird." Accessed May 16, 2014. http://www.festo.com/cms/en_corp/11369.htm.

Sossinsky, Alexei. *Knots: Mathematics with a Twist.* Harvard University Press, 2004.

Stiny, G. "Ice-Ray: A Note on the Generation of Chinese Lattice Designs." *Environment and Planning B: Planning and Design* 4, no. 1 (1977): 89–98. doi:10.1068/b040089.

———. "Weights." *Environment and Planning B: Planning and Design* 19, no. 4 (1992): 413–30. doi:10.1068/b190413.

Stiny, George. *Shape: Talking about Seeing and Doing.* The MIT Press, 2008.

Stiny, George, and James Gips. "Shape Grammars and the Generative Specification of Painting and Sculpture." *Information Processing* 71, no. 1460–65 (1972): 125.

———. "Shape Grammars and the Generative Specification of Painting and Sculpture." In *Information Processing 71.* Ljubljana, Yugoslavia, 1971.

Todd, Mattie Phipps. *Hand-Loom Weaving: A Manual for School and Home.* Rand, McNally & company, 1902.

Waterson, Roxana. *Paths and Rivers: Sa'dan Toraja Society in Transformation.* Leiden: KITLV Press, 2009.

———. *The Living House: An Anthropology of Architecture in South-East Asia.* Tuttle Publishing, 2010.

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