

Formalization, Data Abstraction, and Communication

by

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Submitted to the Department of Architecture on May 9, 1997 in partial fulfillment of the requirements for the degree of Master of Science in Architecture Studies on Design Inquiry.

Abstract

Shape Grammar introduces the algorithm that stimulates the development of form and its meaning in the design process. Since Shape Grammar provides a way of representing form and its meaning as sets of mathematical terms, which are shapes and the different algebra, Shape Grammar has been anticipated for developing an architect's design idea with a computer-aided system. However, its application has been limited in the theoretical analysis of the historical precedents in architecture. Thus, a study of the practical application of Shape Grammar is needed in order to make creative design, in the actual design process, using a CAD system, possible.

Through the experimentation with "making folly," this thesis introduces a model for the application of Shape Grammar to the architectural design process. It presents theoretical foundations, describes the methods of formalization, data abstraction, and communication with Shape Grammar in making designs, and illustrates the process of making folly as the result of this thesis.

The approach is derived from the study of the different definitions of architectural form and the observation that architects explore formal ideas by producing sequences of drawings, which are schema(s). This thesis investigates possible methods of formalization and data-abstraction based upon schema(s) in the architectural design. Also, this thesis proposes the framework for a prototype computer system that efficiently supports the communication between different computational tools. This communication is established by encoding the design process as the result of the data abstraction, which is composed of shapes as mathematical means, and formalizing the architect's design knowledge according to certain compositional rules. Then, an experiment with "Folly"¹ design is performed, based upon the suggested methods for the application of Shape Grammar.

In conclusion, based upon the results of the experimentation, the initial territory, spatial block, and spatial components in the combination between different algebra are proposed as design methods for the application of Shape Grammar in the making of a creative design. Also, existing problems in the making of practical software are introduced.

Thesis Supervisor: George Stiny

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¹A costly but useless structure built to satisfy the whim of some eccentric and thought to show his folly (Vidler, A. 1983)

Acknowledgments

“Transition from knowing into thought...”

The important parts of this thesis were done in continuous discussion with Prof. George Stiny. I appreciate his philosophical and theoretical support during the writing of this thesis.

I also want to thank my wife, Sang-Hee, my parents, and my daughter.

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And the LORD came down to see the city and the tower which the sons of men had built. And the LORD said, "Behold, they are one people, and they all have the same language. And this is what they began to do, and now nothing which they purpose to do will be impossible for them." "Come, let Us go down and there confuse their language, that they may not understand one another's speech." So the LORD scattered them abroad from there over the face of the earth; and they stopped building the city.

Genesis 11:5 - 8

Introduction

The questions about the relationship between designs and their descriptions have provided a jump-off point for developing the architectural design idea. How are the forms synthesized to make up designs? What kind of design knowledge is used to describe designs? And how are designs and descriptions combined to represent architecture?

Rapid developments in the usage of the computer as a design tool have undoubtedly changed the nature of design itself. Nonetheless, the expectation that computer-aided design would increase the architect's understanding of form and meaning in the architectural design process has not been realized. Several design theorists have developed new design methods for accomplishing this expectation with a computer-aided system. "Shape Grammar," one of these new design methods, focuses on the algorithm that animates designs and their descriptions. It provides a theoretical foundation for representing our knowledge and experience of architecture with mathematical means, which are sets of shapes and the combination of different algebra. However, Shape Grammar has so far only been applied to analyzing the historical precedents in architecture. Thus, Shape Grammar has not been regarded as something practical to be applied in the making of the creative design in the actual design process.

This thesis investigates the possible application of Shape Grammar to the architectural design process, and considers the following problems :

- i. What is the design knowledge, and what are the designers' own rules of representing his/her ideas by the architectural form, "not only in what rules the designers use but also in how they use them"¹ ?

- ii. How does the designer apply the design knowledge, and his/her reasoning, not only to develop the design idea, but also to make drawings ?

- iii. Through the making of drawings, how does the designer organize/transform such design knowledge and reasoning into a database/database query that might render the history of understanding and experience for communication in the design process?

- iv. How does the designer integrate different computational tools through a shared database in order to produce the efficient exchange of design knowledge, which stems from "different worlds"² ?

Through experimentation with folly design, a method for formalizing an architect's design knowledge is developed with Shape Grammar. With this formalization, data abstraction is introduced as a tool for dividing the architectural design process. Data-abstraction allows an architect to develop design ideas with sets of shapes. By making the combinations of the data-abstracted information in the different meaning categories, which are the result of the formalization, the communication between different computational tools is established, with sets of shapes as mathematical means in the design process. Then, this thesis proposes a framework for a communication that represents the design process, not only as an assembly of shapes built up according to certain compositional rules, but also as a process of data abstraction in the formalization of the architect's design knowledge.

¹ Schön, 1988

² Goodman, 1978

The proposed framework, which consists of formalization, data-abstraction, and communication, allows an architect to develop a design in four ways.

First, a new transformation can be inferred, from a current sequence of drawings, with the representation of design knowledge because the reason/method of design decision-making can be represented, not only in drawings with shapes, but also in a database with numbers.

Second, existing sequences can be edited by changing the order of the described design knowledge, or by replacing it with different design knowledge.

Third, architects can easily exchange information about different aspects of the same artifact with other professionals.

Fourth, a possible connection between the traditional design process and the computational one can be established.

Through this process, an architect can make his/her own descriptions of the architecture, and then the architecture can be presented to the architect as his/her world.

Chapter I. The Definition(s) of Architectural Form : C

What is architectural form? To answer this question, I begin with the hypothesis that Architecture is the work of the architect. The architect's work exists as a fact by its own substance after architects create Architecture¹ on "earth."² The architect needs his/her own descriptions of the work, *Architecture*³, to communicate Architecture. After the work is cast out to earth by the architect, the work of the architect can no longer be in the architect's "world."⁴ Therefore, architectural form is how the architect establishes his/her own descriptions of *Architecture*. These descriptions, which are established by architectural form, compose the communication in making the boundaries of the communication. Within the boundaries of this communication, the architect has, not only the limitation, but also the freedom, of his/her working. The communication makes understanding Architecture possible. This understanding of Architecture allows the architect to establish the descriptions of *Architecture*. After all, the architect represents *Architecture* through architectural form, and creates Architecture, the work of the architect, through the communication.

However, one can easily find that the above paragraph violates logic for two reasons. First, the architect cannot create Architecture before he/she represents *Architecture* through the architectural form for establishing the communication. Second, the architect cannot represent *Architecture* without Architecture. However, Architecture is always on/in the site. The site exists on earth, not only as it is, but as it would be, because the site is not only Architecture, which is the work of various architects, including God, but *Architecture* that the architect is working on at the site. In

¹ After the work is cast out to earth by the architect, it exists as a thing

² The state of the thing; the thing as it is: the open system

³ The work is cast out to earth by the architect before "Architecture"¹

⁴ The state of the work; the thing as it would be: the closed system of the world-maker

this context, Architecture is created in the communication outlined by the architect's own descriptions, which is established in architectural form, about the architecture that the architect is working on at the site. : *1.1 The formal symbol system*

Throughout the history of architecture, most architects have described the architecture with drawings because of, not only the practical advantages, such as economy and convenience compared to the full-scale real building, but also the formal advantages of developing/representing their ideas. In addition, as the ways of making their descriptions, architects have preferred spatial elements, based upon the visual aspect, rather than upon other sensual aspects. Architectural form can be how the architect establishes his/her own description of the architecture, in the visual aspect, with the drawings. : *1.2 The usage of drawings as the formal symbol system in representing design ideas*

Although the traditional drawings and models are composed of volumes in three dimensions (space) in actuality, the drawings are regarded as the sets of points, lines, and planes in two dimensions (plane) usually. Since the traditional models gave physical user-interface in space as the real building did on earth, the drawings and models were easily separated from one another, although architects assumed the volume in space from such things as perspective or axonometrics, and imagined the height of the walls from the plan drawing.

With the help of advanced computer technology, computer-aided design(CAD) systems have provided architects with several advantages, such as almost unlimited memory capability, an efficiency in modifying designs, and convenience in exchanging information. As the use of CAD

has increased in the architect's design process, the architect has needed to translate the drawing from the formal symbol system into a mathematical symbol system. In other words, the architect has started to view the architectural form as the composition of shapes, which are spatial elements as mathematical means, with the descriptions based upon their relation. Architectural form is how the architect establishes his/her own records of *Architecture* with the composition of spatial elements in one of various dimensions as mathematical means. : **1.3 From Form into Shape**

To create *Architecture*⁵, the architect describes *Architecture*⁶ in his/her world, although *Architecture* exists as a fact on earth. Therefore, one architect's descriptions are quite different from those of others', because of the difference of each architect's world. The architect's knowledge and experience constitute the boundaries of his/her world. The architect describes *Architecture* from his/her knowledge and experience.

Therefore, within the boundary of the architect's own knowledge and experience, architectural form is how he/she establishes the description of *Architecture* with the sets of spatial elements in one of various dimensions as mathematical means, which are with the description of their compliance.

: **1.4 Design knowledge as the sets of shapes with the description of their compliance**

⁵ The work is cast out to earth by the architect

⁶ The work is cast out to earth by the architect before "Architecture" ⁵

1.1 The Formal Symbol System

In the process of defining the formal symbol system, I will briefly review the philosophical background of the world and earth, and explain how existing differences between the world and the earth introduce the formal symbol system into architecture. In addition, with Goodman's five ways of world-making, I will introduce the notational symbol system as the structure for describing the world.

As Martin Heidegger mentions in his "Basic Writing," the difference between the thing and the work always exists as the difference between what it is and what it is meant by/what it would be. In other words, there exists the difference between the earth and the world. Compared to earth, as an open system -what it is- Wittgenstein introduces the world as a closed system that allows meaning inside -what it would be/ what it is meant by- in his "Brown Book." He suggests the describing not explaining things in the world as the way to communicate between the worlds of different peoples.

From this point of view, Architecture is the work of the architect. However, the architect's work, Architecture, exists as a fact by its own substance after architects create/cast out Architecture onto earth. The architect needs his/her own descriptions of the work, *Architecture*⁷, to communicate Architecture, because the work of the architect can not be in the architect's world⁸ after the work is cast out to earth by the architect. Now, the architect needs a way to establish his/her own descriptions of *Architecture*. Several semiologists have tried to understand the cognitive process in the manipulation of symbol systems. The manipulation of symbol systems has been employed in

⁷ The work is cast out to earth by the architect before Architecture

⁸ The state of the work; the thing as it would be: the closed system of the world-maker

different categories as illustrated in figure 1.1.1. In this thesis, I will regard the sets of spatial elements as the formal symbols of *Architecture*, and the notational symbol system as the prototype of an architectural world-making paradigm.

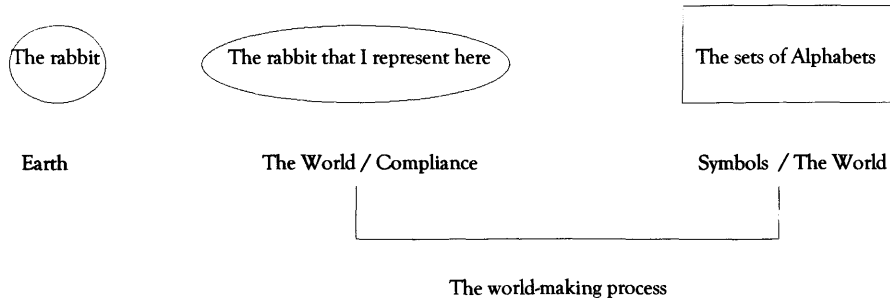
Figure 1.1.1 Symbols in the different categories

Category	Language		Architecture	Music
Domain	in Time	The sets of Phonemes	The sets of spatial elements	The sets of tonal composition
	in Plane	The sets of Alphabets and marks		The sets of scores
Name	Linguistic Symbols		Architectural Symbols	Musical Symbols

In his “Words, Works, Worlds,” Nelson Goodman, one of the semiologists, suggests that the notational symbol system be the structure for describing the world. By definition, a symbol is a thing to denote the world, not the earth, because the earth will disappear as soon as the notion of symbol appears. The denoted world is a “compliance.”⁹ The notational symbol system is a system that basically consists of a finite number of individual symbols. The system functions by the relation between the different sets of symbols, based upon specific orders or rules.

⁹ the thing denoted by a symbol (Goodman, N. 1976)

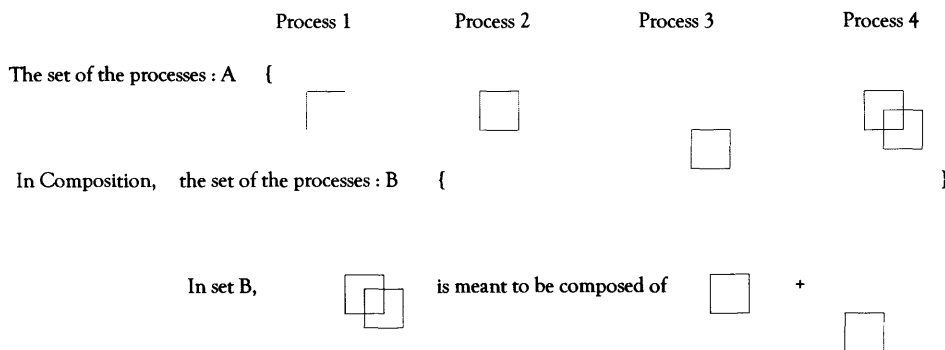
Figure 1.1.2 the example in the notational symbol system



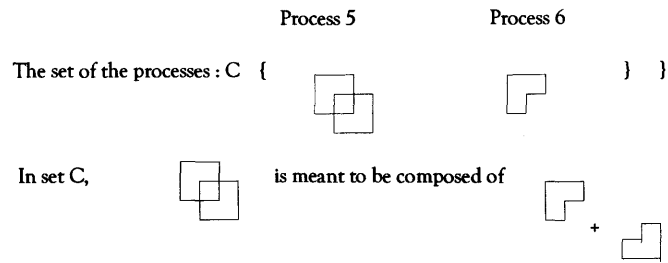
Although the individual symbol has its own semantic and syntactic definition, the set of the individual symbols is redefined by the ways of world-making. Here, I interpret Nelson Goodman's five ways of world-making in Shape Grammar.

First, with "composition and decomposition," he mentions that the notational symbol system distinguishes the semantics and syntax of symbols in the set of processes of composing and decomposing that counts as works. The set of processes is not restricted by the chronological order not by the set of working processes. The examples are described in figure 1.1.2.

Figure 1.1.2 Composition and Decomposition

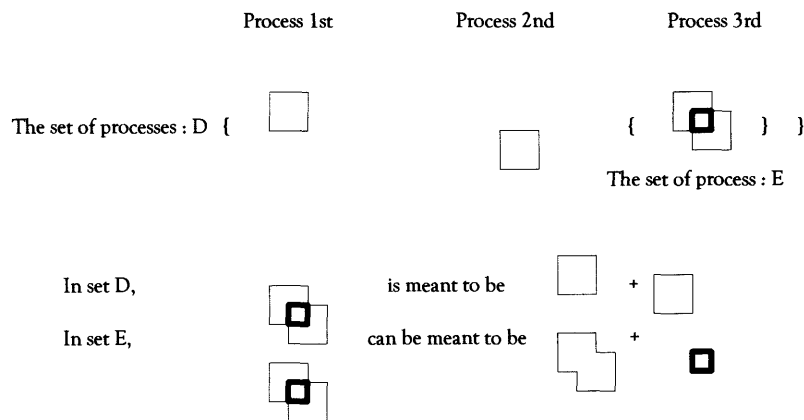


In Decomposition,



Second, with changing interests and new insights, the visual weighting of features creates the differences of syntax and semantics in the different sets of the processes of composing and decomposing. It means that different visual weighting implies a different world in the working process.

Figure 1.1.3 Weighting

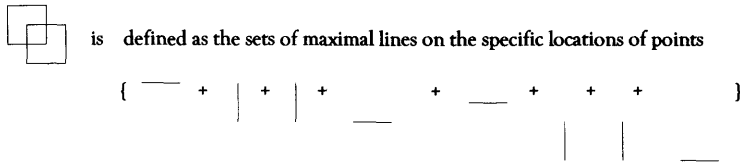
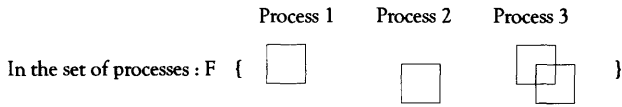


Third, the worlds of different representational systems differ in the order of composition and decomposition. Figure 1.1.4 shows an example of the difference resulting from ordering.

Figure 1.1.4 Ordering

When the representational system of the world is defined as follows:

- i) The representational system of the figure is defined as the sets of maximal lines in a plane
- ii) The maximal line means the maximal entity recorded between two points



rather than the union of two squares { □ + □ }

Fourth, the world that we make usually consists of significant fragments and clues that need a huge supplement of information because our capacity for overlooking is virtually unlimited and our capability of representation, when making worlds, is relatively limited.

Figure 1.1.5 Emergent Shape



An Emergent Shape resulting from the deletion of information needs the supplementation of information to be determined.

In the process of representing the figure at left, the information of the figure is deleted from the three dimensional entity (volume) in time, a duck or rabbit on

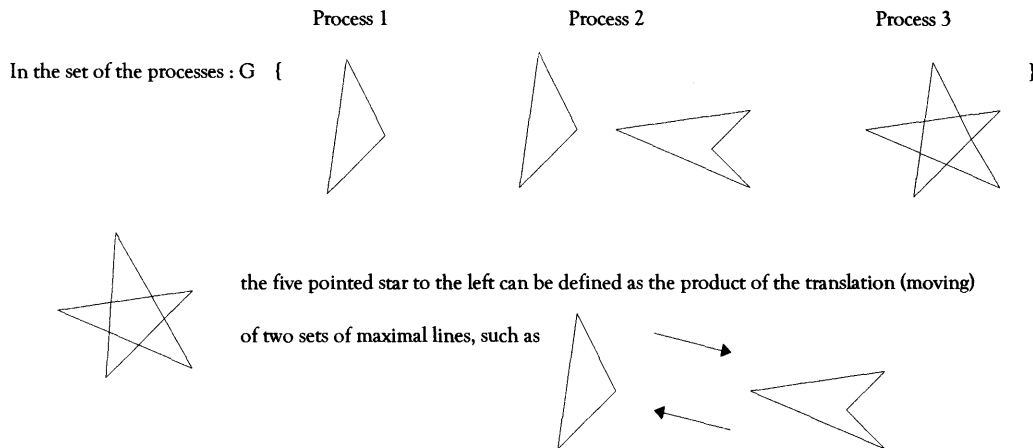
earth, into a one dimensional entity (the sets of lines) in two-dimensions (plane), the drawing on the paper. There must be ambiguity in defining the nature of this figure because the world in the plane is established with the deleted information. Therefore, this figure cannot be determined in common. This means that since the world is created with a deletion of information, supplementation of the information is needed for representing the world. However, the need for supplementation of information introduces perception, which is the great creative power of designing. This power is used to develop design ideas. I will talk about perception in chapter 2. In addition, perception of the figure is included in the set of { something of duck, something of rabbit}, not in the set of { something of tiger,

something of elephant, ...) This suggests that the deletion of the information is made from the defined deformation of the world, which is established with the proper mapping.

Fifth, when the deformation is defined in the proper “mapping”¹⁰ procedure, each deformation in different sets can be described with this mapping. Therefore, some changes are reshaping or deformation that may be considered to be either a correction or distortion of the world.

Figure 1.1.6 Deformation / Transformation

When the deformation of the individual shape composed of maximal lines is defined as the Euclidean transformation, such as moving(translating), mirroring, rotating, and scaling,



Here, I suggest the architectural design to be an architect’s own world-making by architectural form. In this thesis, the formal symbol system will be regarded as a notational symbol system in the

¹⁰ a technical term meaning the relationship between two things, in this case between the controls and their constructional movement in the world. (Goodman, N. 1978)

architecture category. Goodman's ways of world-making with a notational symbol system provides a philosophical foundation for me to make the world of "Making-Folly" in chapter 4 of this thesis.

1.2 The usage of drawing as the formal symbol system in representing design ideas

This section reviews the development of the usage of drawings: the elements of making drawings, drawings in architecture, and drawings as architectural elements of representing the architectural design ideas.

In his "On the Art of Building in Ten Books," Leon Battista Alberti explains the idea of the "lineament"¹¹ as how the architect represents his/her inner worlds with lines and angles in drawings. Since his idea of lineament functions as a formal symbol system to project/represent an architect's idea, making drawings with the lineaments can be understood as making the architect's design world of a formal symbol system. After all, he used the sets of lines and angles as formal symbols and their orientation and conjunction as the deformation/transformation of the architect's inner world, when he made drawings. In other words, Alberti used the lineament to create a formal symbol system to making drawings.

Andrea Palladio explains the "Beauty"¹² to be the result of the formal symbol system. In his "The Four Books of Architecture," he suggests that beauty can be examined through the model or draught, which are the formal symbol systems for representing beauty. His notion of beauty, in the

¹¹ "It is quite possible to project whole forms in the mind ... by designating and determining a fixed orientation and conjunction for the various lines and angles." (Alberti, L. B. [1452] 1994)

¹² "Beauty will result from the form and correspondence of the whole, ... and all necessary to compose what you intend to form." (Palladio, A. [1721] 1965)

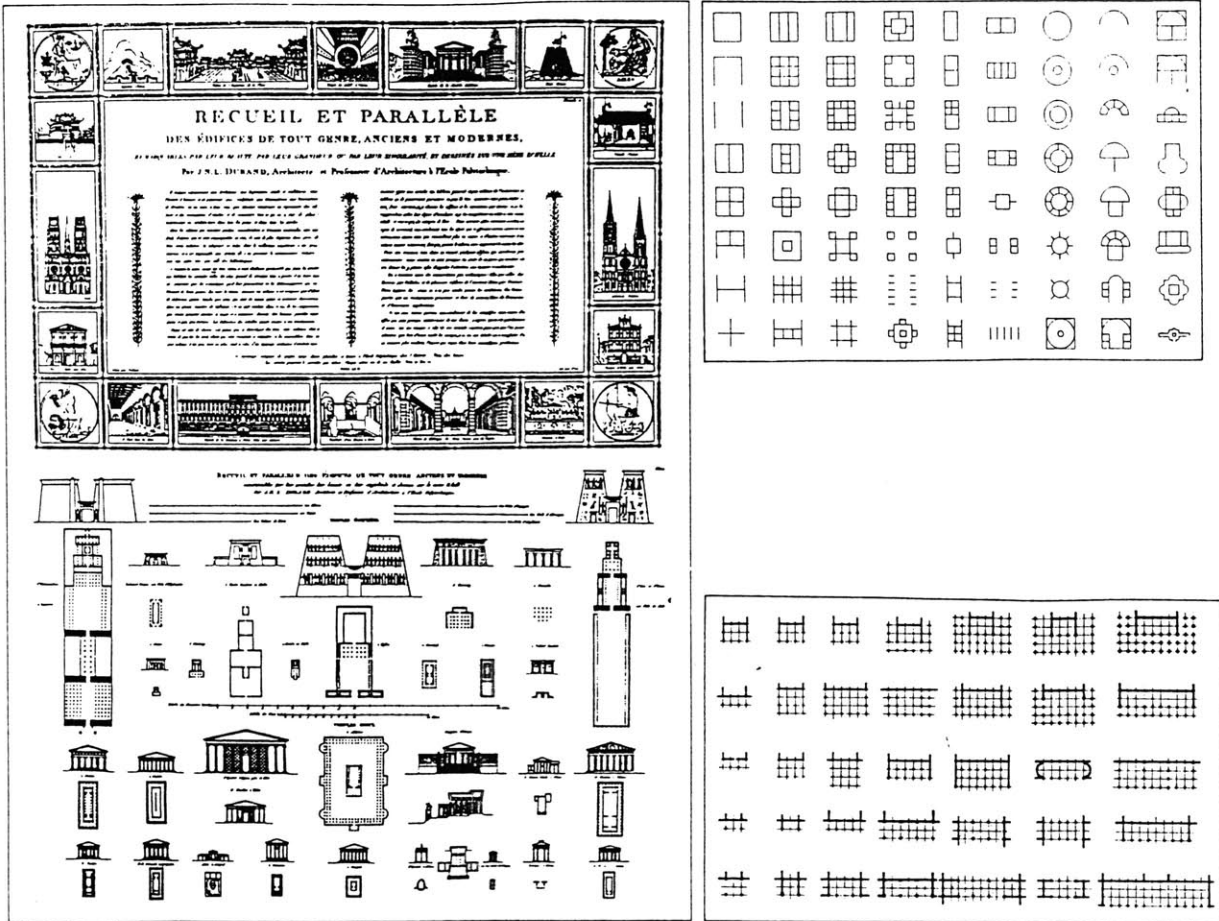
aspect of making beauty, shows more close relation between the draught and the formal symbol system because whatever beauty is, it is represented through the draught. Palladio shows the usage of drawings to be the formal symbol system, and the different sets of drawings, such as plans, elevations, and sections, to represent the different aspects of beauty.

In the “Recueil et Parallèle des Édifices de Tout Genre,” Durand surveys a large number of significant historic buildings. He presents them in the form of plans, elevations, and sections according to their “type.”¹³ Figure 1.2.1 shows examples of his drawings.

¹³ In this thesis, type is regarded as the combination of two different symbol systems, which are the formal symbol system and the linguistic symbol system. The combination results from the type-maker's world-making process.

Figure 1.2.1 Some examples from the Recueil and the Précis

- I. Front piece and the first plate of the Recueil (From Durand, J.N.L. 1981)
- II. Basic plan shapes (From Durand, J.N.L. 1802)
- III. Porches (From Durand, J.N.L. 1802)



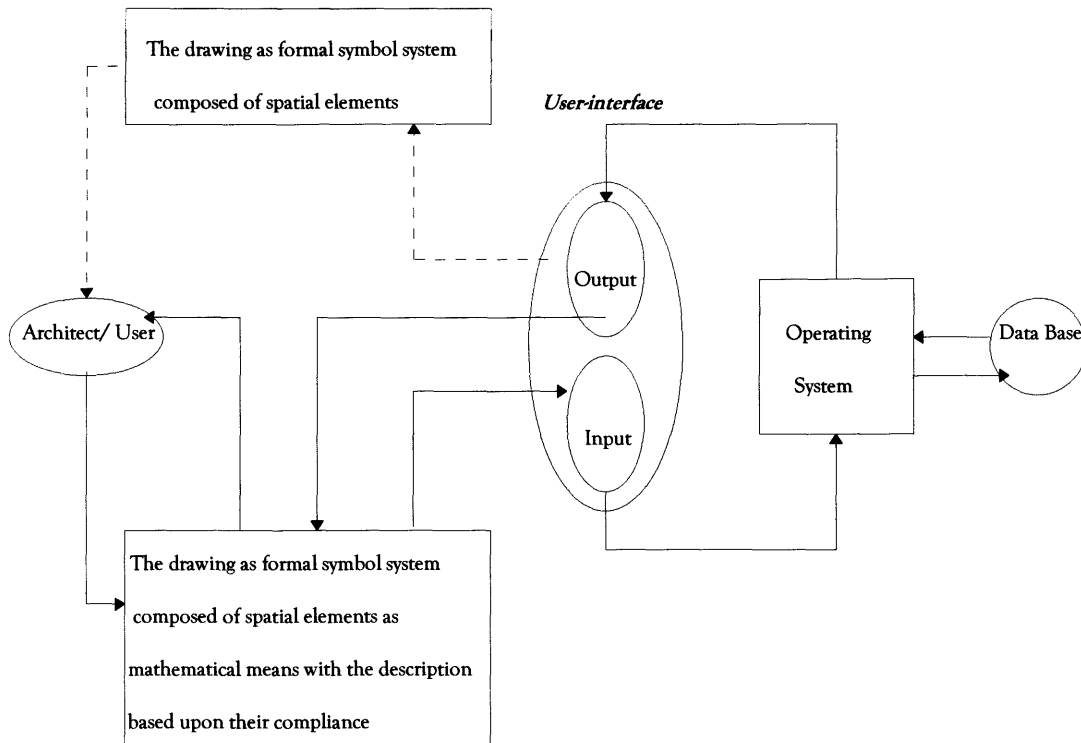
Through the drawings, he describes the table of architectural species for showing the implied method of making them. Durand applies the drawings to explain all building types systematically. This means that in making drawings he not only describes the work of the architect, but also reorganizes another world, which is a systematic rearrangement of building types, in describing the work of architect. Durand's system of form-making is illustrated in the "Précis des Leçons d'Architecture." In this book, he suggests that *Architecture* should be derived through the systematic combination of its essential components. Walls, columns, and openings are considered to be basic elements for constructing various architectural spaces. From this point, Durand starts to arrange the formal symbols, which are the sets of spatial elements, in the architectural meaning. In return, he develops the drawings of architectural elements as the formal symbol system. After Durand explains the drawing as the formal symbol system for combining a minimal set of architectural elements with a finite set of compositional rules, the drawing becomes not only a symbol representing Architecture, but also a tool as the architectural elements for making drawings individually. The notion of the drawing as a tool says that the drawing itself exists as the sets of the formal symbols which are independent from the architectural meaning. In other words, the drawing itself starts to be manipulated as the sets of formal symbols, which are composed of the sets of spatial elements (points, lines, and planes on two dimensions) with or without architectural meaning. Now, the drawing can exist as formal symbol, composed of the spatial elements on the earth.

1.3 From Form into Shape

Rapid developments in the usage of the computer as a design tool have undoubtedly changed the nature of design itself. The computer-aided design (CAD) system has provided architects with several advantages: almost unlimited memory capability, efficiency in modifying designs, and convenience in exchanging information. As the use of CAD has increased in the architect's design process, the architectural representation method has changed from drawings and models, done with pencil & paper and knife, glue & basswood on earth, to the drawings and models done with the computational tools in the world of the machine.

However, the usage of CAD has been not entirely as successful as architects expected because it has been a hindrance in the architect's working process, with the conflicts between two different symbol systems: the architect's world in formal symbol system, and the world of the machine in mathematical symbol system. The world of the machine is a combination of two different symbol systems: the world of user-inter face and the world of the operating system inside the machine. Since the world of the operating system is composed of mathematical symbols, a drawing has to be translated from spatial elements into spatial elements as mathematical means, in order to make a world of design. Figure 1.3.1 shows the existing different worlds between user and the machine.

Figure 1.3.1 The existing different worlds



Finally, for the usage of CAD in the architect's design process, the architect needs proper translations from the formal symbol system into the mathematical symbol system. How to make a world that allows this proper translation has been an important factor in the development of the architect's usage of the CAD system. In other words, in using the CAD system, the architect should represent his/her work by its own formal symbol system composed of the sets of spatial elements as mathematical means in one of various dimensions. In this thesis, Shape is introduced as the sets of spatial elements formed by mathematical means in one of various dimensions..

1.4 Design knowledge as the sets of shapes with the description of their compliance

To create “Architecture,”¹⁴ the architect describes “*Architecture*”¹⁵ in his/her world, although *Architecture* exists as a fact on earth. Therefore, the architects’ individual descriptions are quite different from each other, they depend on what each architect’s world is. Since an architect’s knowledge and experience constitute the boundaries of his/her world, the architect describes *Architecture* out of his/her design knowledge and experience.

What is the architect’s design knowledge? In general, the architect’s design knowledge encompasses the architect’s own past experiences, aspirations, and perceptions, as well as the shared and empirically validated experiences and practices of their discipline as a whole.

To answer this question further, I begin with how an architect can use design knowledge his/her work with a CAD system. The architect’s design knowledge constitutes the boundaries of the world, where the work of architect is. The architect uses his/her design knowledge in his/her working. It means the architect has represented his/her design knowledge with his/her own formal symbol system. However, it is difficult to agree that the architect’s design knowledge can be completely represented by its own formal symbol system composed of shapes, because the architect cannot introduce his/her design knowledge, such as meaning, function, and material, by mathematical means only. Thus, the description of compliance in the linguistic symbol system is accompanied by shapes. After the architect’s design knowledge is recorded by shapes and the

¹⁴ The work is cast out to earth by architect

¹⁵ The work is cast out to earth by architect before “Architecture”⁹

description of compliance, the architect will apply his/her design knowledge using the advantages of the CAD system.

I don't define what the architect's design knowledge is. I just introduce a way to represent design knowledge. The definition of design knowledge will be made by the architect who represents his/her design knowledge in his/her working, with the proper symbol system, because "design knowledge" is totally based upon the architect's individual world. However, after the architect's design knowledge is recorded in the CAD system, we'll share the architect's design knowledge through communication, which is done with different computational tools.

Chapter 2. Shape Grammar

: *t(Shape Grammar) <= (the definitions of Architectural form)*

In the previous chapter, I introduced the architectural form and the shape; the architectural form is the way of establishing the architect's own description of Architecture with the sets of the spatial elements, which belong to one of various dimensions, as mathematical means with the description of their compliance, and the shape is the sets of spatial elements, in one of various dimensions, as mathematical means.

This chapter will review "Shape Grammar"¹ to provide a foundation for the study of the architectural form as the sets of shapes with a description of their compliance, and the applications of Shape Grammar. This chapter begins with an observation of drawings in the process of architectural design, and introduces a series of "schema"² not only *for developing design*, but also *for making drawings*. : *2.1 Schema(s)*

Through the introduction of Shape Grammar, I will explain how to represent design knowledge with schemas. : *2.2 The Introduction of Shape Grammar*

In addition, the previous research will be reviewed in order to the usage of Shape Grammar in architecture. : *2.3 Previous research on Shape Grammar*

¹ George Stiny, one of the founders of Shape Grammar, named it in his "Pictorial and Formal Aspects of Shape and Shape Grammars," 1975

² a diagrammatic representation that mediates perception

2.1 Schema(s)

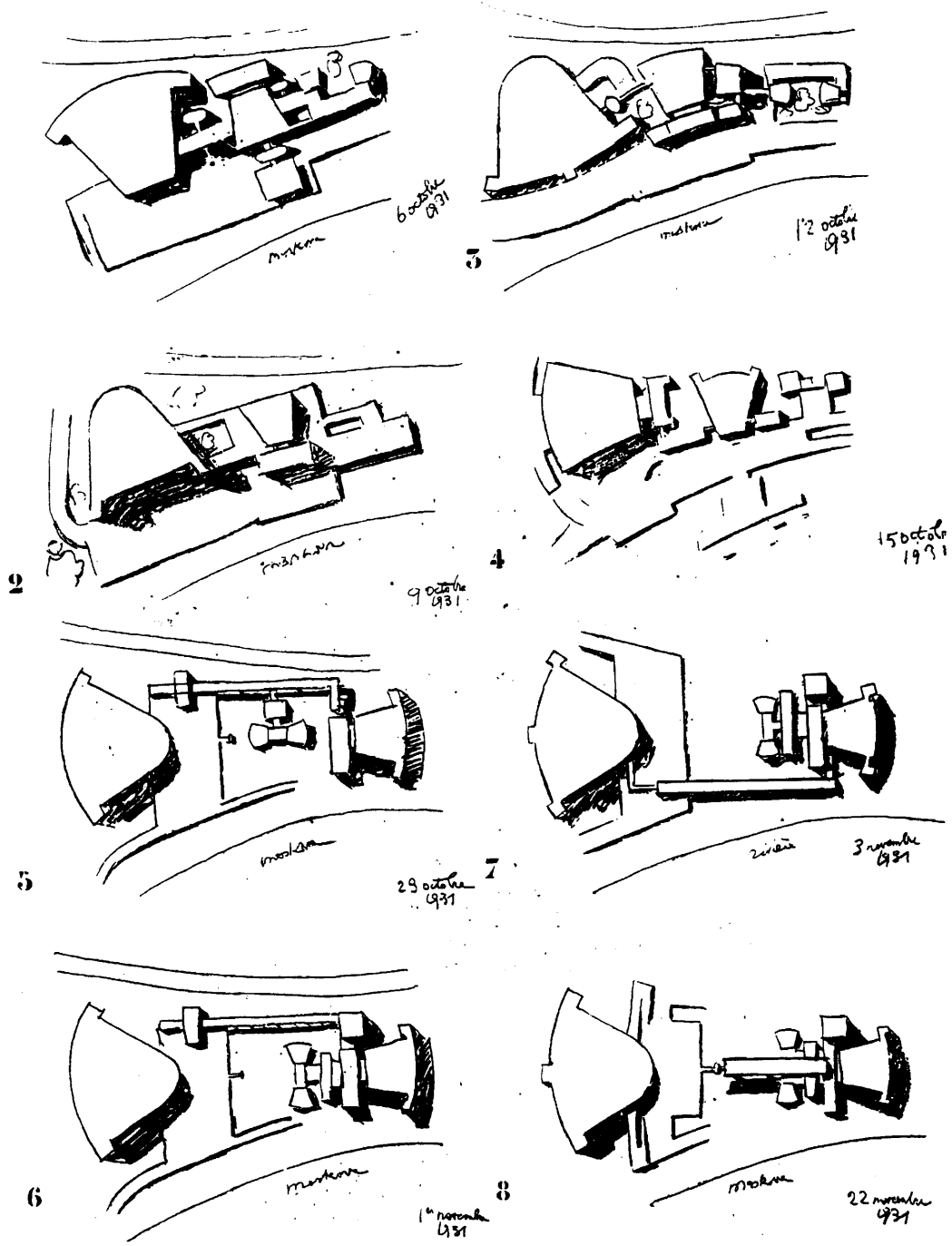
By definition, a schema is a diagrammatic representation that mediates perception. In the architectural design process, many architects have used drawings as their schemas for developing design ideas to create Architecture, and have established their own descriptions of their works in the process of making drawings to communicate with their works. In other words, schemas have been used, not only to develop design ideas, but also to make their drawings. Figure 2.1.1 shows the usage of drawings as schemas in design process. In figure 2.1.1, as can be seen, each drawing brings about the subsequent drawing as a schema and the elements of each drawing remains a part of the new drawing. The drawing as schema mediates the architect's perception when he/she is developing designs, and the drawing transforms its spatial elements into the subsequent drawing in the process of making drawings. However, how a schema mediates an architect's perception and transforms itself into another schema still remains a question.

Figure 2.1.1 Le Corbusier, Palace of Soviets, Moscow, 1931-32, comparative drawing of the successive solutions for the articulation of the buildings, from 6 October to 23 November, December 1931. (From Cohen, J.L. , 1992)



The final drawing for the Palace of Soviets

The sequence of drawings as Schema



As explained in the previous chapter, a drawing is a formal symbol system composed of sets of spatial elements. An architect establishes the formal symbol system, which is the world, with a series of drawings. In the process of establishing his/her world, the architect as a world-maker uses five ways to make the world: composition & decomposition, weighting, ordering, deletion & supplementation, and deformation (transformation).

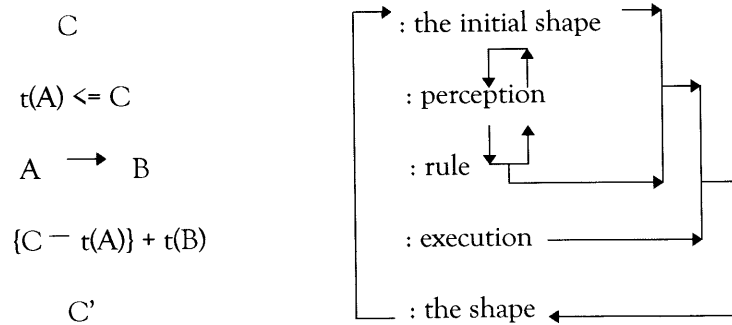
Since the architect's capacity for overlooking is virtually unlimited, and our capability of representation is relatively limited in making worlds, the architect usually establishes his/her drawing with deleted information. Therefore, to represent his/her ideas with drawing, the architect needs for the supplementation of information for the drawing itself. Now, the architect needs his/her perception to provide the supplementation of information. In his "The Later Works of John Dewey," John Dewey defines the perception providing the supplementation of information as "the controlled or directed transformation of an indeterminate situation into one that is so determinate in its constructions and relations as to convert the elements of the original situation into a unified whole" (Logic : The Theory of Inquiry, Volume 12).

According to Nelson Goodman's idea of deformation, the directed transformation leads the changes of the sets of spatial elements in the drawing into the subsequent drawing with some reshaping or deforming. Thus, the drawing functions as a schemas for the architect's directed transformation and then it changes into the subsequent drawing with the architect's directed transformation. The directed transformation will be defined as perception in section 2.2.2.

2.2 The Introduction of Shape Grammar

By definition, Shape Grammar is a visual grammar that represents a designer's "algorithm"³ for developing various shapes in the design process. Shape Grammar is composed of "algebra"⁴ of shapes and the descriptions pertaining to meanings. It generates shapes in terms of what we see. Shapes are manipulated according to the rules that allow parts of shapes to be defined and changed recursively to conform to given spatial relations. In this way, the architect can organize his/her ideas of developing shapes by applying rules to the initial shape, which is usually one of the schemas in the architectural design process, and can manipulate these rules during the design process with the computational tools. Figure 2.2.1 shows the basic algorithm of Shape Grammar.

Figure 2.2.1 The algorithm of Shape Grammar



³ In Mathematics, algorithm means step by step problem-solving procedure, specially an established, recursive computational procedure for solving a problem in a finite number of steps.

⁴ the set of objects with relations and operations

2.2.1 Shape and Algebra in Shape Grammar

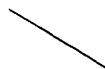
C : The initial shape

By definition, shape is composed of basic elements. Basic elements are the sets of the spatial elements, in one of various dimensions, as mathematical means. The spatial elements are points, lines, planes, and solids. Every spatial element has an environment that it belongs to. The environments range from zero to three-dimension, and are known as location, length, area, and volume. Every spatial element, except for a point, has a boundary that introduces the maximality of the spatial elements. The boundaries are: points for a line, lines for a plane, planes for a solid. In Shape Grammar, the algebra of shape is applied to schemas. The set of objects is composed of shapes. The relations are embedding (\leq , $=$), union (+), difference (-), and intersection (\cdot) in the Boolean operation. In this way, the arithmetic is directly applied to the design. The operations in Shape Grammar are moving(translating), rotating, mirroring, and scaling in Euclidean transformation, which is represented as $t(\text{shape})$. Shapes are determined by the finite sets of maximal points, lines, planes, or solids. Maximal means the maximal entity formed by the boundaries of the perceived sets of spatial elements.


Figure 2.2.1.1 The Basic Elements

The environment of this illustration is defined in space U^3

● A point has a location as its entity in U^0



A line has a length as its entity and points as its boundary in U^1

A plane in U_{23} has an area as its entity and lines as its boundary (after this example, I'll represent a plane as  (enclosed lines)



A solid has a volume as its entity and planes as its boundary in U_{33}

The Maximal elements in U_{12}



When the left figure is defined by the sets of lines in the plane, the maximal lines can be defined by how one perceives the sets of spatial elements. For example,



A



B



C

In case A, eight points introduce the eight lines. In B case, twelve points introduce the twelve lines.

In case C, the twelve points introduce the twelve lines again but with different sets of shapes.

: how to perceive the sets of spatial elements will be explained in chapter 2.2.3.

In Shape Grammar, the universal algebra of shape is represented as U_{ij} . In U_{ij} , i represents the dimension of the spatial elements (0: point, 1: line, 2: plane, 3: solid) and j the environment of the spatial elements (0: point, 1: line, 2: plane, 3: solid). The boundary of the U_{ij} is usually defined as $U_{i-1, j}$ except for U_{0j} . The boundary of U_{0j} is defined by the location, which is the entity of the point, in the environment of the point. To represent the architect's design knowledge properly, the description of compliance in the linguistic symbol system is accompanied by shapes in Shape Grammar. This description is also represented by changing the underlined part of \underline{U}_{ij} . In Shape Grammar, the name of the algebra can be defined depending on the user's needs. In addition, every description can be represented by a combination of different algebra. For example, when C_{ij} is defined as the combination of the universal, structure, and material algebra based upon the user's need, it can be represented as $U_{ij} \times S_{ij} \times M_{ij}$. The usage of the combinations of the different algebra will be explained in section 2.4 "Formalization."

2.2.2 Perception in Shape Grammar

$$t(A) \leq C$$

When the initial shape is defined as C , perception is introduced in the process of $t(A) \leq C$.

In other words, in the process of defining the embedding (part) relation between the transformed shape A and the initial shape C , the architect's perception has to be involved in order to generate the transformation of the shape A because the architect doesn't get the shape A itself. After all, the algorithm of Shape Grammar needs the architect to transform the shape A , and define the relation between the initial shape C and shape A , before the shape A itself is not defined yet. This means that the algorithm of Shape Grammar intentionally provides an undetermined situation to the architect in order for the architect to maintain his/her perceiving process continuously. In addition, as defined in section 2.2.1, shapes are determined by the finite sets of maximal points, lines, planes, or solids. Thus, the notion of maximality functions as a constraint when defining shape A . In Shape Grammar, the emergent shape means shape A , developed by the architect's perception from the initial shape C , in the process of $t(A) \leq C$. In return, since the emergent shape A is defined by the architect's perception, which is "the directed and controlled transformation," the architect already knows how to operate the emergent shape A inside the initial shape C in Euclidean transformation. After all, the architect can define, not only the emergent shape, but also the operation of it, in $t(A) \leq C$. About this "directed transformation", George Stiny says: "Directed transformations are such that each has the same characteristic form in which specific operations are ordered to put observation and action into functional correspondence" (*The Automation Based Creative Design : Pedagogical Grammar*, p131).

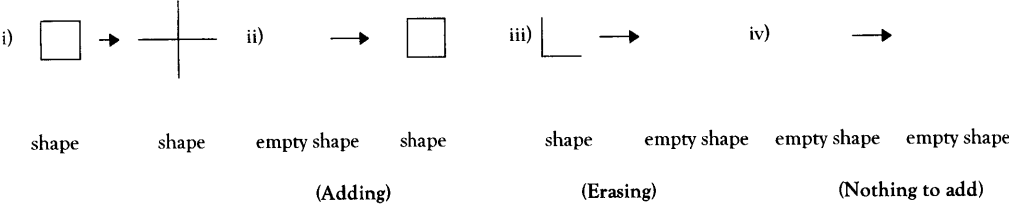
2.2.3 Rule in Shape Grammar

$$A \longrightarrow B$$

By definition, in Shape Grammar, a rule is composed of two shapes, which can be empty shapes. The left part of the rule is installed by the emergent shape discerned from the initial shape in the process of defining the part relation between the transformation of shape A and the initial shape C. In Shape Grammar, how to decide/define the right part of the rule still remains a problem to be solved. However, I'd like to regard the right side of the rule as a place for the architect's creativity, not as an arbitrary decision. This problem will be studied in section 2.4 "Folly-Making".

Figure 2.2.2.1 An example of the rules

In U12,



After the rule is defined, the left part of the rule is transformed by the user's perception of the initial shape. When the left part is the empty shape, the shape, which is the right part of the rule is added to the initial shape.

2.2.4 Execution in Shape Grammar

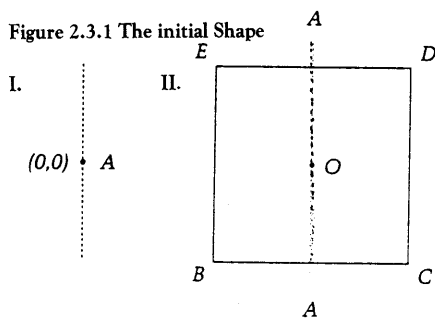
$$\{ C - t(A) \} + t(B)$$

After the initial shape and the rule are defined, the operations such as difference (-) and sum (+) are performed on the initial shape. Through this execution, the architect gets another shape C'. With this recursive algorithm, an architect develops his/her design idea and the drawings evolve from the design.

2.3 Previous research on the application of Shape Grammar

In "Palladian Grammar" (Stiny & Mitchell, 1978), Stiny & Mitchell explain how to apply the algorithm of Shape Grammar to analyze an existing building's plans. They represented the generation of original ground-plans of villas, which are Italian Renaissance country houses, designed by Andrea Palladio. Through Palladian Grammar, the rules, which not only originated from Palladio's design but were also defined by Stiny & Mitchell, produce all the villa plans that Palladio designed. Figure 2.3.1 shows the defined rules in Shape Grammar. Furthermore, the variations generated by this grammar have been accepted as true instances of Palladian style by architectural historians, although Palladio didn't design the variations. Figure 2.3.2 represents how the defined rules are applied to make drawings, and illustrates developing schemas with these rules.

Figure 2.3.1 The initial Shape

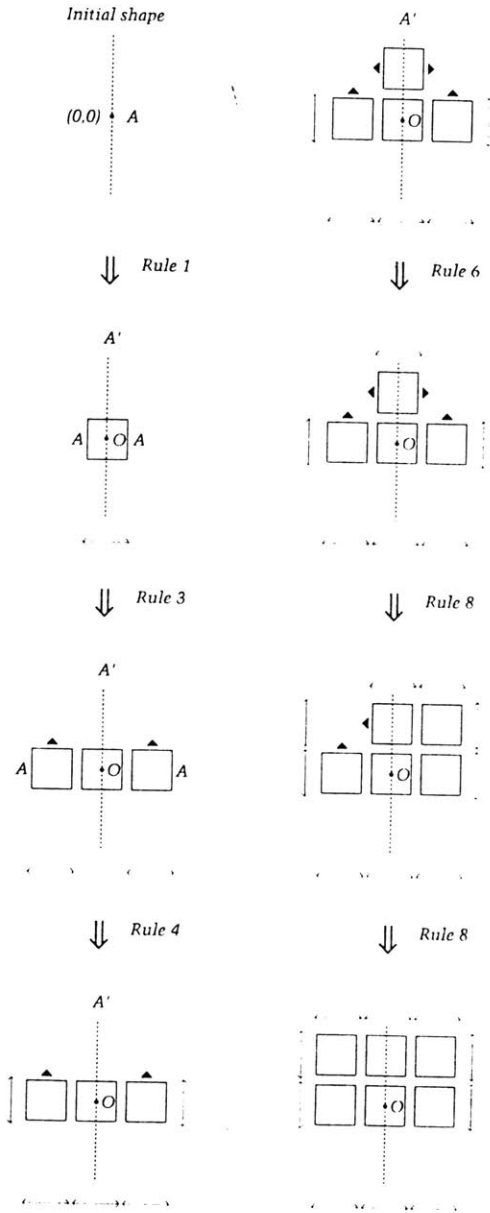


- I. The initial shape from which all villa plans are generated : an axis through a labeled point
- II. The association of labels with points and with ends of lines segments
- III. The application of the rules to generate a small tartan grid
- IV. The derivation of the Villa Malcontenta's pattern of openings

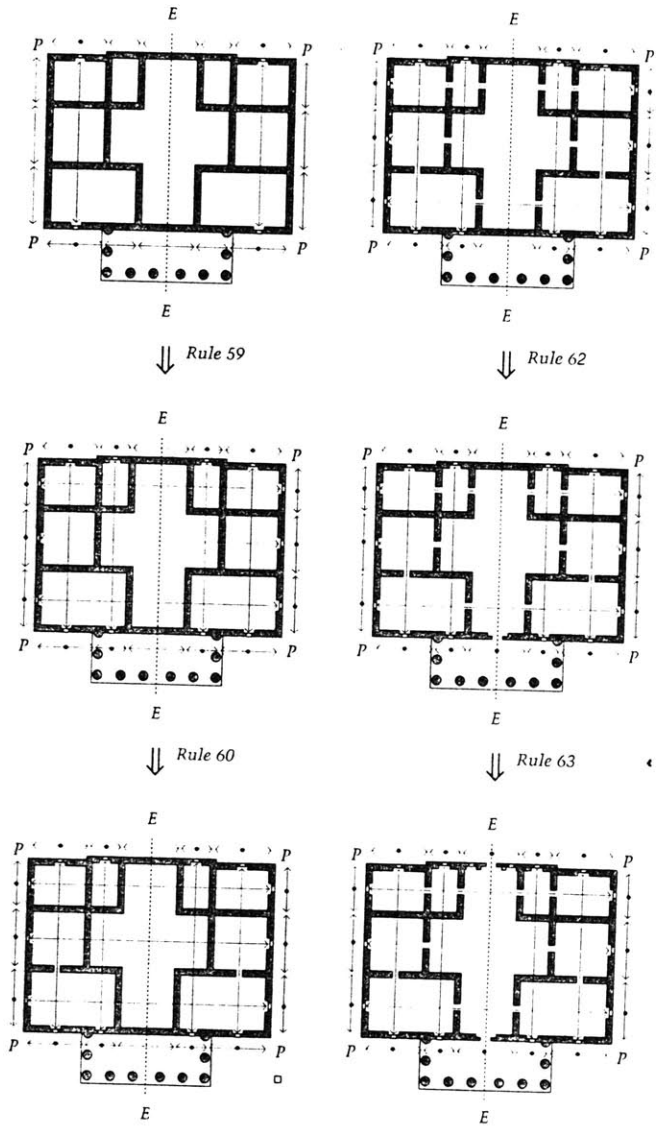
(From Mitchell, W.J., 1989)

Figure 2.3.2. Rule Application (From Mitchell, W.J., 1989)

III.



IV.

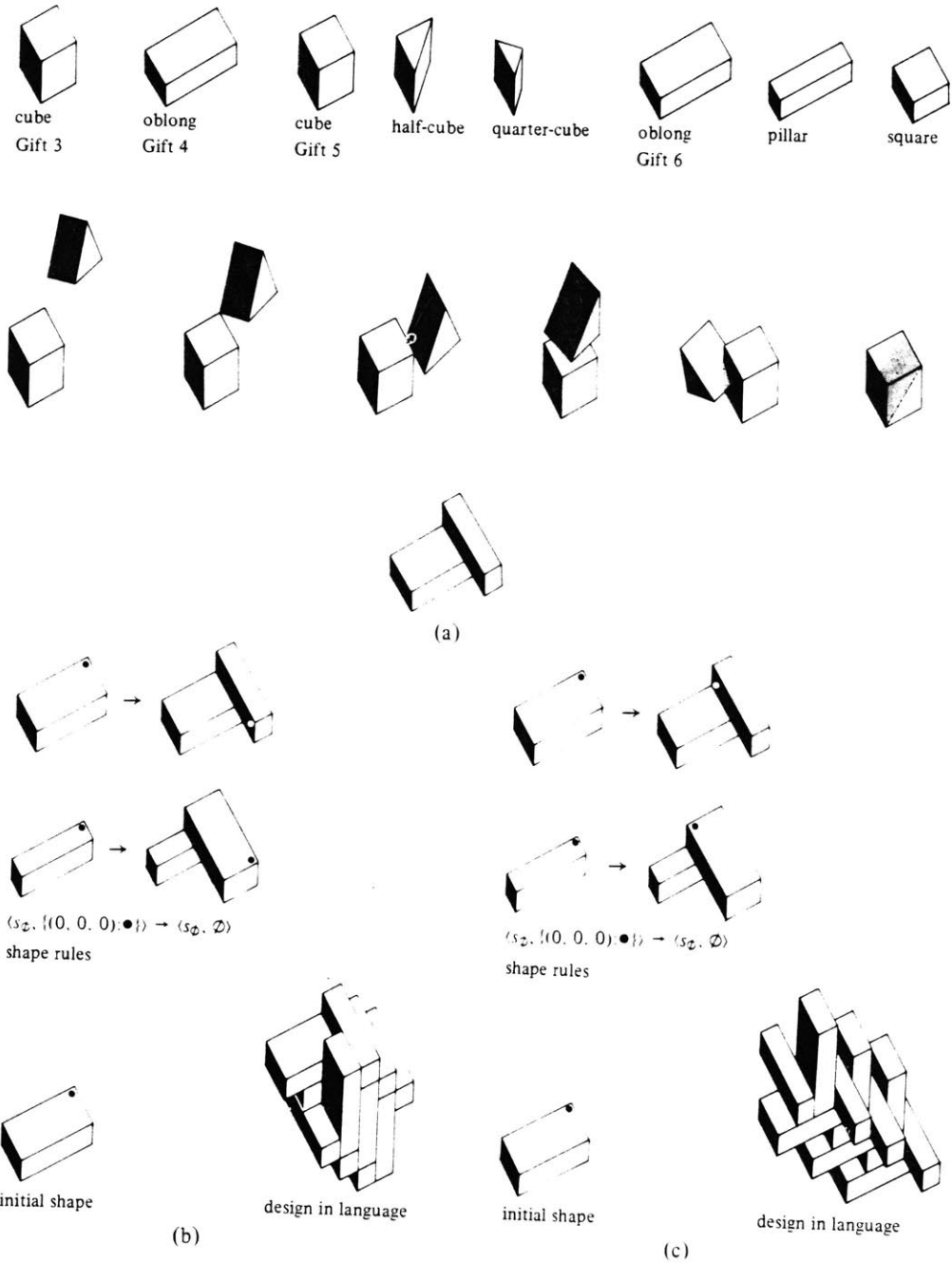


As can be seen in figure 2.3.1, the dotted lines play an important role in making the right part of the rule an axis, direction, division, or indication. As I mentioned in section 2.2.3, the right part of the rule has been difficult to define with Shape Grammar. However, the usage of the dotted lines has been an initiator for creating the geometrical relations between the left and right side of the rule. In architectural design, many architects have drawn regulating diagrams/lines to explain the geometrical relations as Stiny and Mitchell use the dotted lines in Palladian Grammar. In his “*Toward a New Architecture*,” Le Corbusier describes the regulating lines : “a regulating diagram offers a tangible form of mathematics, the welcome sense of a visible order. The choice of a regulating diagram determines the basic geometry of a piece of work, one of its principal characteristics. The choice of a regulating diagram is one of the decisive moments of inspiration; it is an essential procedure in architecture.” The idea of the regulating diagram will be when representing the rules and schemas in the process of “Folly-Making.”

In “*Froebel Kindergarten Grammar*” (Stiny, 1980), Stiny examines the possibilities for constructing designs with shapes in the given vocabulary according to these spatial relations. Within Froebel’s categories of form, which are several types of playing blocks, he represents various results of Froebel block’s combinations. Through the design process with Froebel blocks, Stiny defines the rules fixed by the spatial relations between these blocks, and then applied the rules to create design. In the end, he describes the creating design as the sequence of rule definition and rule application, and introduced the possible application of Shape Grammar to spatial design (see figure 2.3.3).

Figure 2.3.3 Froebel Kindergarten Grammar (From Stiny, G., 1980)

- I. The vocabulary of shapes given by Froebel's building gifts
- II. Spatial relation and shape grammars comprised of rules in terms of (a)

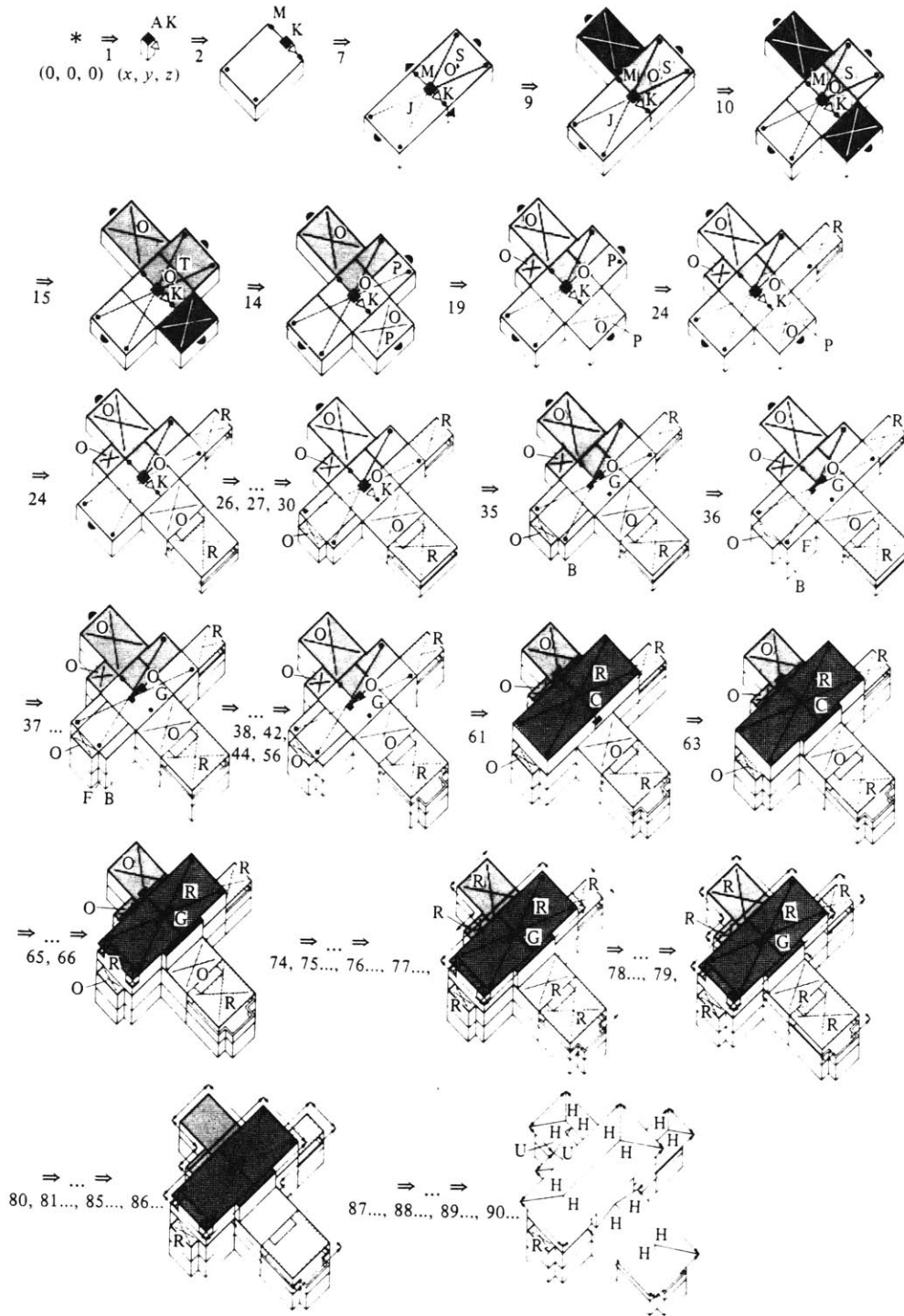


As can be seen in figure 2.3.3, after Stiny defines the several blocks as basic objects for rule application, he develops schemas in three dimensions. Each schema was initially a set of blocks in Froebel Kindergarten Grammar. From the initial set of blocks, he defines the rules based upon the spatial relations between the different blocks. Then, he starts to construct blocks by applying the defined rules to the initial set of blocks. At the initial stage of the architectural design process, the architect manipulates the simplified spatial blocks, which is based upon his/her developing plans, sections or sketches, to understand the three dimensional organization of his/her design. In return, the manipulation of the spatial blocks influences the overall organization of the architect's design. In this aspect, the idea of Froebel Kindergarten Grammar can be applied to develop the overall organization of the space unit in the [Making-Folly] design process. The details of this application will be illustrated in chapter 4 .

In the Shape Grammar of Frank Lloyd Wright's prairie houses, Koning & Eizenberg combined the rule application in organizing three dimensional blocks, and the application of the rules generated from the existing building. They showed the possibility of applying Shape Grammar to the analysis of historical precedents in architecture. The application of this grammar, used for local assemblages of the Prairie house will be use to describe "Making-Folly." Figure 2.3.4 shows some examples.

Figure 2.3.4 The Language of the Prairie houses (From Koning, H. and Eizenberg, J., 1981)

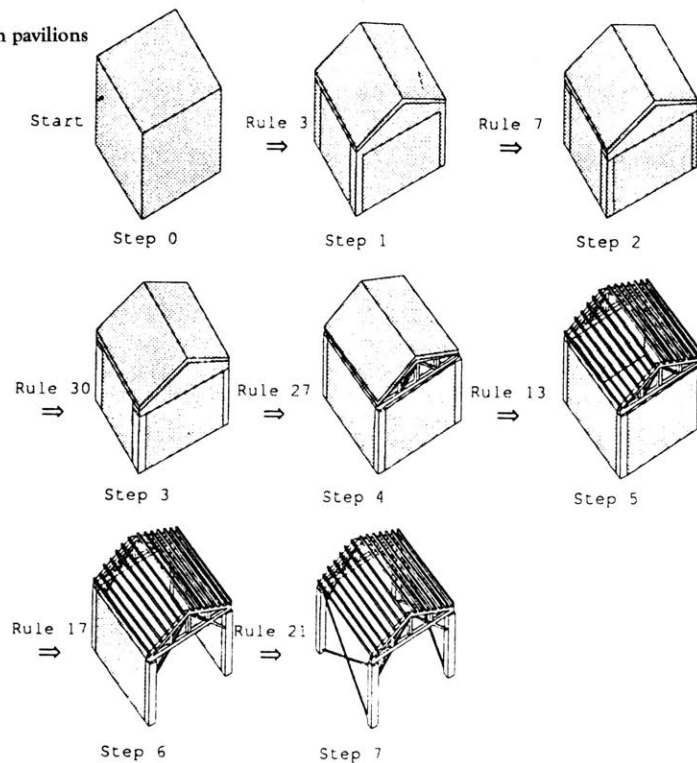
The generation of a prairie-style house according to the Shape Grammar of Koning & Eizenberg



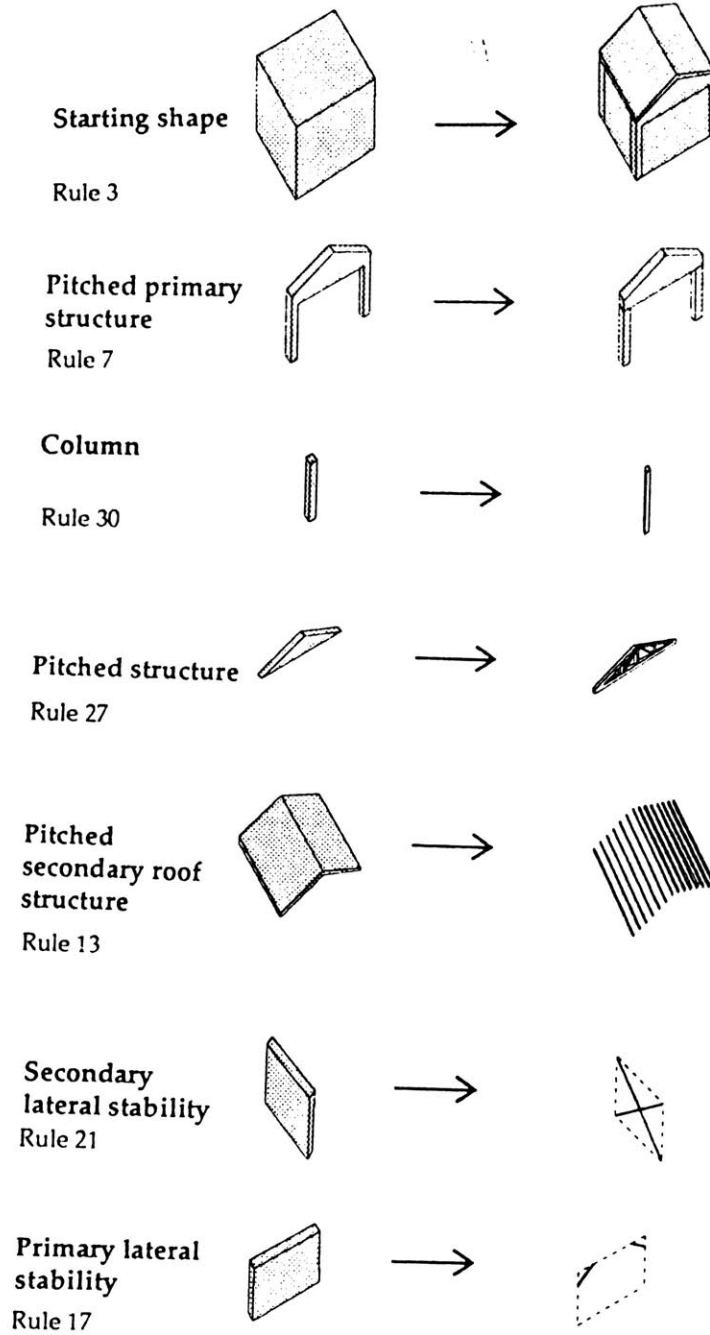
In “The Artifact Grammar,” Mitchell develops the idea of three dimensional organization in Froebel Kindergarten Grammar with structure and material descriptions. After he defines the structural vocabularies, which can be components of the artifact/building, he establishes the rules, composed of the shapes from the structural vocabularies. Then, the rules are applied to construct the artifact with Shape Grammar. After all, with this Grammar, the architect can use the set of three-dimensional arrangements of shapes, which is defined by the structural aspect, as both sides of the rule in Shape Grammar. In other words, Mitchell introduces the set of the three-dimensional arrangements of shapes in the categories of knowledge-representation : the structural, material, and financial aspects. Figure 2.3.5 shows the examples. In “Making-Folly”; the set of three dimensional arrangements of shapes will be defined with the combination of the several knowledge-representations needed for the architectural design.

Figure 2.3.5 Artifact Grammar (From Mitchell, W.J. , 1994)

i) Derivation of a design in the language of garden pavilions



ii) The defined rules in Artifact Grammar for the derivation of a design (From Mitchell, W.J. , 1994)



Chapter 3 “ Folly-Making” : *Shape Grammar* → *Folly-Making*

This chapter suggests, as the foundation for “Making-Folly,” formalization as the method of defining the architect’s design knowledge. Data abstraction is defined as a tool for developing design ideas into sets of shapes with a specific description of the architect’s design knowledge within this formalization. By creating combinations of data-abstracted information, various design developments can be achieved, not only in developing design ideas, but also in making drawings with the computational tools. Then, such information in the categories can be integrated into the proposed framework of communication.

3.1 Formalization

By definition, in “Folly-Making,” formalization is a method that allows the architect to define his/her design knowledge with symbols. Through the process of formalization, the architect can make his/her own categories of meaning. After the possible meaning categories are defined, his/her design knowledge is described as the combination of the different categories, or the combination of different items in the same category. In other words, formalization introduces meaning into the specific boundary of the earth, and the world of architecture is bestowed on the architect for “Making-Folly” as sets of shapes and different algebra.

As introduced in chapter 1, Nelson Goodman suggests five world-making methods : composition & decomposition, weighting, deletion & supplementation, ordering, and transformation. In Shape Grammar, the combination of the different meaning categories is provided as the foundation for the ordering of the architectural design. The ordering itself can vary with the individual architects because they each have their own unique knowledge with which to create the hierarchy and categories in his/her ordering. However, the method of ordering might be accepted in common if the method is established logically. Shape Grammar is provided as the method for describing *Architecture* composed of the combinations of different sets of shapes, and different algebra. With this function, an architect can establish his/her own descriptions of design knowledge. Thus, by formalizing his/her design knowledge in the design process, the architect can describe his/her design knowledge by the combination of different meaning categories. Formalization begins with describing the defined items in the specific meaning categories of the architect's design knowledge.

Dijyw : when the basic elements are represented with a spatial definition, the elements can be described as Dijyw. In Dijyw, i means the domain of the basic elements , j the environment of i, and y means the categories of the spatial definitions.

((0 <= i, j <= 3), (1 <= y <= n, for "making-folly", n= depends on user's need) (1 <= w <= n))

Dijyw = Uij x Sijyw, when Sijyw = Uij x My x Iw

My means the defined category including the defined items

Iw means the specific number of items in the category

Sijyw means the symbols represented in Uij that pertain to the specific item w in category y

The algebra based upon the spatial definition

: Pijyw = Uij x S33yw, when S33yw = U33 x My x Iw

(here, since y is restricted to the one category of the spatial definition that I will make,
I will represent P_{ijyw} as P_{ijw})

The algebra based upon the structure

: $T_{ijyw} = U_{ij} \times S_{33yw}$, when $S_{33yw} = U_{33} \times M_y \times I_w$

(here, M_y is restricted to the Structural knowledge that I have)

The algebra based upon the color

: $C_{ijyw} = U_{ij} \times S_{23yw}$, when $S_{23yw} = U_{23} \times M_y \times I_w$

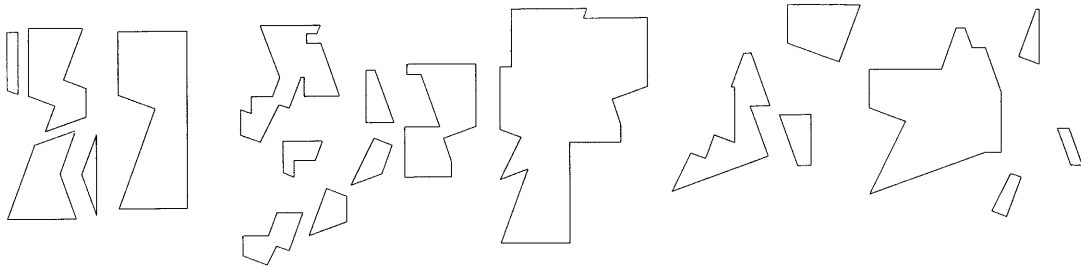
(here, since y will be restricted to the one category that I will make,

I will represent C_{ijyw} as C_{ijw})

The process of formalization can vary with different architects because the definition of design knowledge depends totally upon the individual architect. However, the method of formalization can be shared in common. When an architect finds his/her own way of formalizing, he/she can change the method itself with possible symbols for formalizing in Shape Grammar. After establishing his/her meaning categories with basic items, the architect manipulates the specific shape with different meanings. This manipulation provides the design developing ideas that help the architect evolve his/her schemas because the specific shape with the defined meaning must be the deleted information in explaining itself. At this point, the architect asks the supplementation of this shape and the architect's perception answers with the emergent shape. Thus, formalization provides not only a way of representing the architect's knowledge, but also a way to introduce the deleted information. Also, through the process of formalizing the architect's knowledge, he/she can create data-layers with data abstraction based upon the meaning categories in CAD systems for communication. Figure 3.1.1 shows examples of formalization in "Making-Folly."

Figure 3.1.1

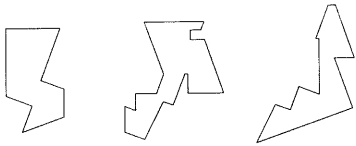
The initial territories in U12



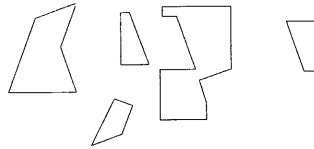
The categories of the planes based upon the spatial definitions

In U23,

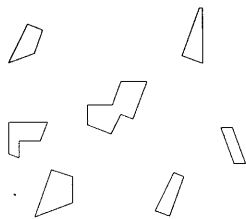
1. enclosed planes : P333



2. The open planes : P334



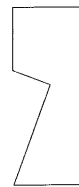
3. The voids and connectors P339 & P335



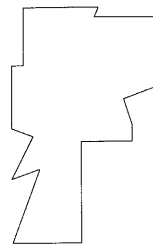
4. The solids P3310 5. The space plane P3311



5. The outlined planes of the combination of the proposed planes with the definition of Layers



L331



L332



L333

3.2 Data Abstraction

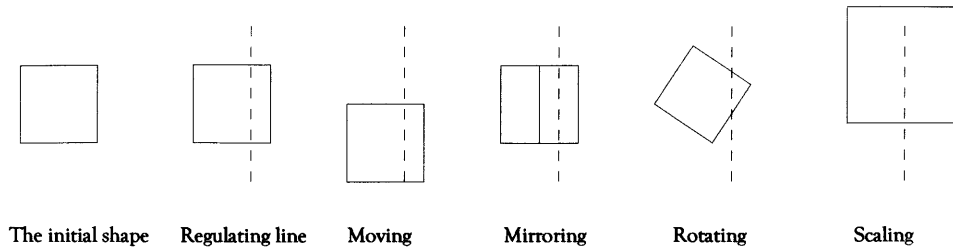
By definition, data abstraction is a method of dividing the architectural design process and developing design ideas into sets of shapes with descriptions drawn from formalization. In the traditional design process, the architect develops its schemas from the site analysis, and puts them into the specific design. In the data abstraction for “Making-Folly,” the architect can define each design step as the combinations of different algebra, which are formed by shapes and symbols in Shape Grammar. Thus, through data abstraction, the architect can develop schemas with shapes, and each schemas can be represented by the shapes. In addition, the architect can reorganize the items in the formalized category with shapes as mathematical means.

In “Making-Folly,” the spatial meaning is accepted only in U33. This means the architect regards sets of basic elements as shapes when he/she develops shapes from U12 to U33. Thus, the enclosed line drawings can be the initial territories that define the boundary of the plane. After the plane is defined by the territories, it evolves the boundary of the spatial block to make the spatial organization of folly in U33. The other line drawings support the architect’s schemas as descriptions in U12. By organizing the relation of the shapes of U12, U23, and U33, the architect can control the schema as a spatial block.

In U12, the idea of regulating diagrams is applied to analyze the site for “Making-Folly” as a description to develop the initial territories. The description of the regulating diagram contains the basic information about Euclidean transformation in Shape Grammar. This information is the direction of the translation, the axis of mirroring, and the base point of rotating and scaling. The

regulating line is represented as the dotted lines in “Making-Folly.” Figure 3.2.1 shows the information about the regulating diagrams as a description.

Figure 3.2.1 The regulating diagrams as a description in U12

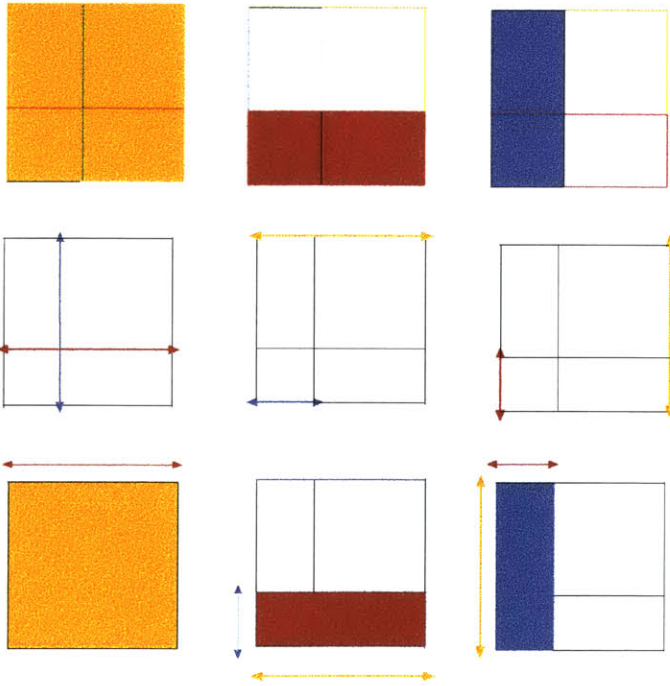
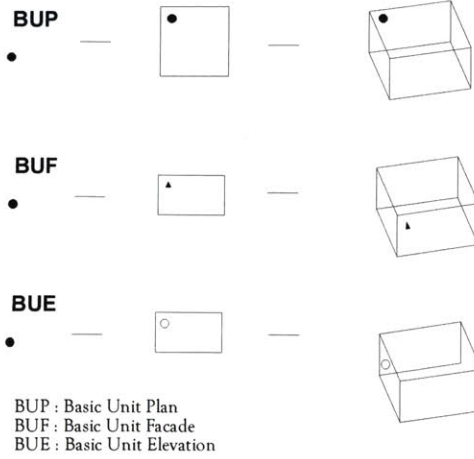


After the architect defines the initial territories in U12, he/she can make a combination of the initial territories (the sets of shapes in U12) and the formalized meaning categories (such as the spatial definitions and the layers, which is based upon the height of the spatial block). With the formalized meaning categories, the architect can provide the right part of the rule : $A \rightarrow B$

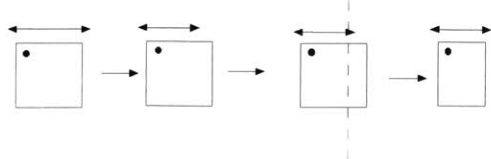
Through this process, the architect combines sets of shapes as the date abstracted information and the rule in Shape Grammar.

In U23, after the boundary of the plane is defined by the initial territories, the architect can develop the spatial blocks in “Making-Folly.” By combining the initial territories and the layer definition, the architect can introduce the spatial blocks in U33 and change the spatial block by the modification of the initial territories in U12 because the specific relation is established with the notion of the boundary in the process of making the combination between the spatial blocks and the initial territories in the layer definition. Figure 3.2.2 shows schemas for controlling the basic spatial unit.

Figure 3.2.2 The Schemas for controlling the basic spatial unit



When the basic unit is defined by the controlling schemas, the basic unit can be controlled as in the right-hand diagrams.



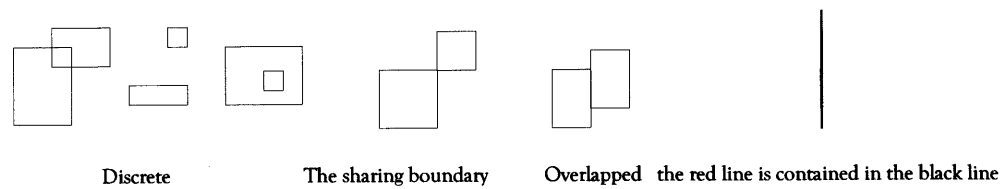
Examples :



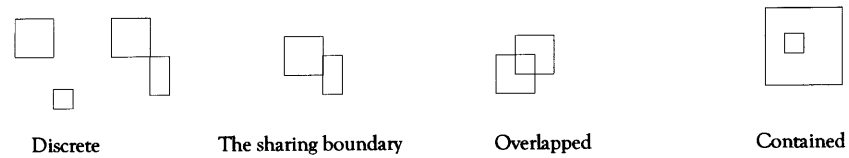
In U33, since each defined spatial block represents a different meaning category in a different combination of algebra, the architect can develop the design by combining the different spatial blocks with different algebra. In this process, the boundary relation is introduced in order for the architect to modify the spatial blocks in the spatial definition, because the spatial definition is defined by the boundary relation of these spatial blocks. Deciding the boundary relation between the spatial blocks, the architect can trace the development of the shapes from U33 to U12 and modify the initial territories. Figure 3.2.3 shows the basic boundary relations.

Figure 3.2.3 The boundary relations

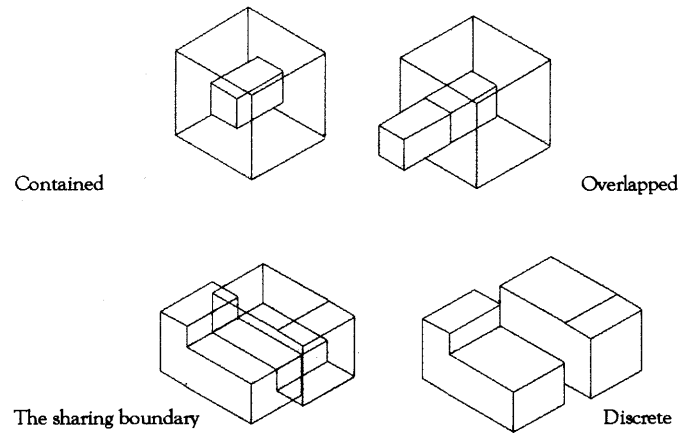
In U12



In U23, to explain the relation, the description is restricted to the XY plane.



In U33,

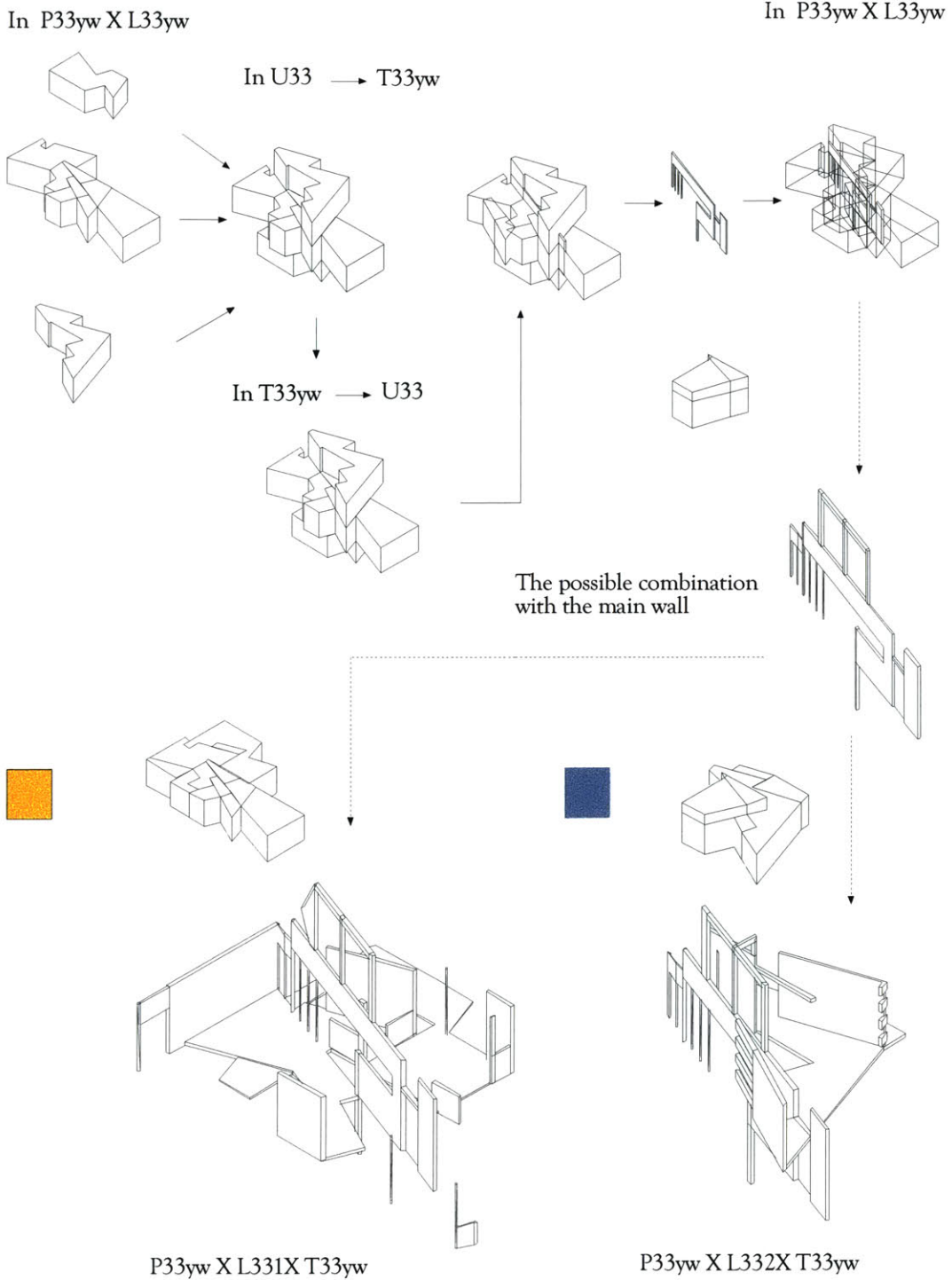


After the modification of the initial territories, the architect can make the new combination for developing his/her design. Through this transition between the different environments of the shapes, the architect can also find the schemas as the result of the combination of different algebra. Figure 3.2.4 shows the combination of the different algebra.

With the formalization and data abstraction, the architect can proceed with the design in two ways. First, the architect can find clues from each of the schemas in the combination of the different algebra when developing the design idea. Second, since the process of formalization and data abstraction provides several categories of meaning, and the items, which are the shapes as mathematical means, in the category, the architect can record his/her design knowledge onto the computational tools with different data-base layers when making drawings.

Figure 3.2.4 The Combination of different Algebra

The different algebras can be combined using several meaning categories
 For example, when there are defined categories of the structural knowledge, the spatial components can be developed as follow :



3.3 Communication

In the computational tools, after the data-abstracted information is recorded in the specific meaning categories as the items, this information can be manipulated in the data-base layers according to the defined categories. Also, the specific items are defined as sets of numbers because the architect has already defined the individual schema as sets of shapes. As defined in chapter 2, these shapes already have entities, which are the location, length, area, and volume, for defining themselves. The framework of the integration of communication is based on each step of the developing schema in the process of data abstraction. Figure 3.3.2 shows the relation between user-interface and database in the proposed framework. In this framework, the data-abstracted information is transported to the specific categories, which consists of sets of layers. Thus, the architect can change the data-base layers by creating a new relationship between the different meaning categories (see figure 3.3.1).

Figure 3.3.1 The possible integration of the data-abstracted information into the framework

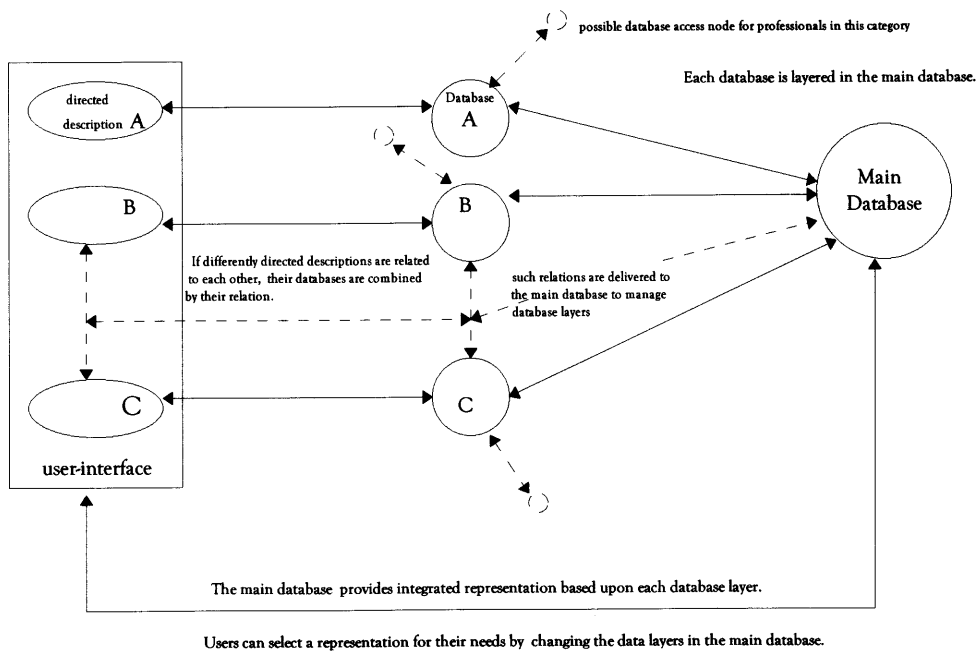
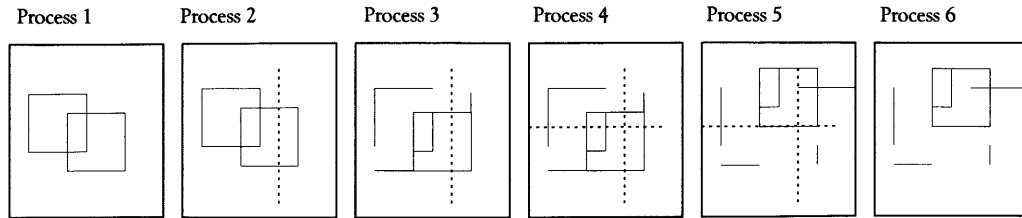


Figure 3.3.2 The relation between user-interface and database in the proposed framework

1. user-interface



2. database (not main database)

about	Process 1	Process 2	Process 3	Process 4	Process 5	Process 6
	: recorded as { }	recorded as { }	recorded as the same shape but as the sum of different subshapes { }			
	: empty	{ + }	{ + }			
	: empty	empty	{ + }			
	: empty	empty	empty	{ + }	recorded as same shape but as the sum of different subshapes { + }	
	: empty	empty	empty	empty	{ + }	
	: empty	empty	empty	empty	empty	{ }

Chapter 4 “ Making-Folly”

: {(the definitions of the architectural form) - (Shape Grammar)} + “ Folly-Making”

This chapter illustrates the experimentation with “Folly-making” that uses formalization and data abstraction. The initial process of “Making-Folly” begins with a study of the defined site. After the site analysis and site configuration, site formalization is introduced for developing the spatial grids.

Based on these spatial grids, possible combinations of the spatial blocks are explored. In this developing process, the spatial grids are defined by different names. After one of the spatial grids is defined as Part of the folly, this grid is data-abstracted using Shape Grammar.

The result of this data abstraction is compared to already defined grids in order to introduce the initial territories for three-dimensional design development. In this process, several meaning categories for “Making-Folly” are formalized.

The defined meaning categories are composed of sets of shapes. With this formalization, each data abstracted shape is manipulated by the architect’s own combination of the different meaning categories. The manipulation of the defined spatial blocks in the combined algebra provides schemas between U12 and U33.

After the architect performs this formalization and data abstraction, Architecture is bestowed to the architect as the result of computation made in his/her world.

4.1 Site

The site for “Making-Folly” is defined as the world, at the MIT University Park on Massachusetts Avenue in Cambridge. This defined site is analyzed in the conventional design ways such as view, direction, the relation between the surrounding buildings, and circulation. After the site analysis, the possible Parti and regulating diagrams are selected from the site configuration. Using the Parti and regulating diagrams, site formalization begins with Shape Grammar.

4.1.1 Site Analysis

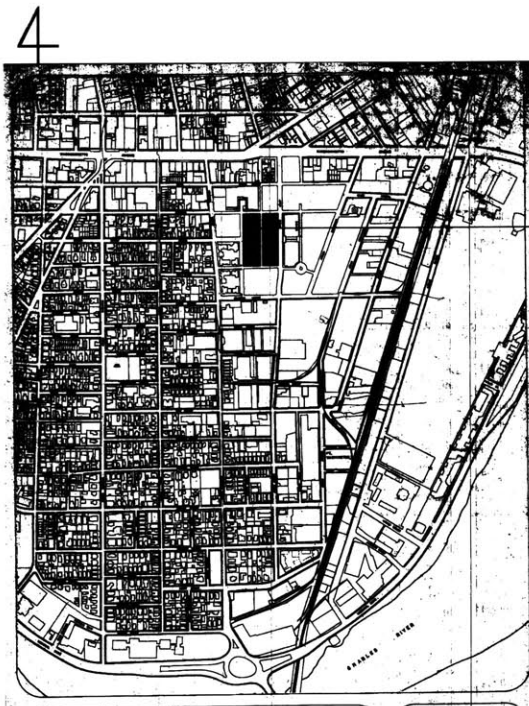
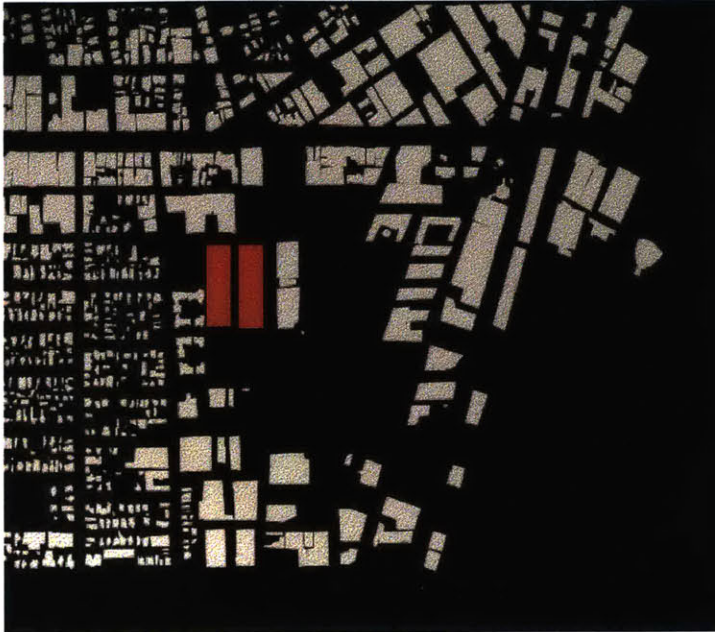


Figure 4.1.1.1 Site in U12

the proposed site

In site analysis, the existing axis and geometric relations are explored. The relation between the surrounding buildings, and the circulation, are explored in figure 4.1.1.2.

Figure 4.1.1.2



As can be seen in this figure, the small and large buildings are located in the different direction the site.

In U33

1



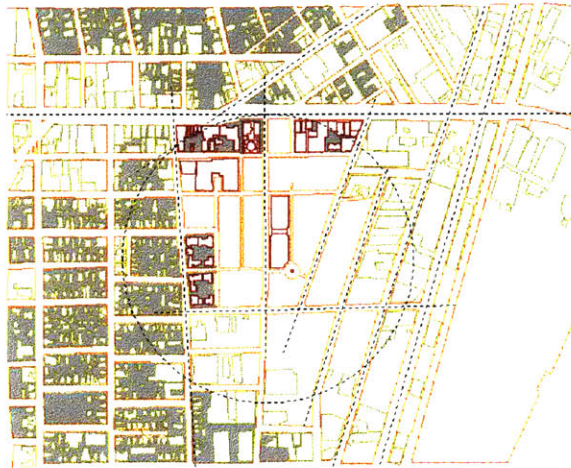
This figure shows the existing axis of the plane. At this point, the definition of the height of the volume and the axis of the buildings can be combined in U23.

2



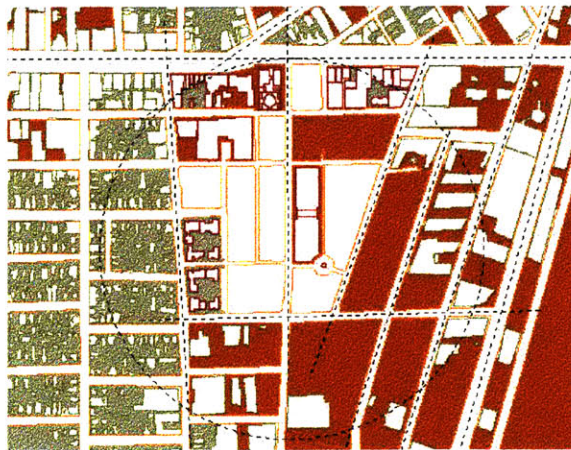
In U12

3



In U12 X U23

4

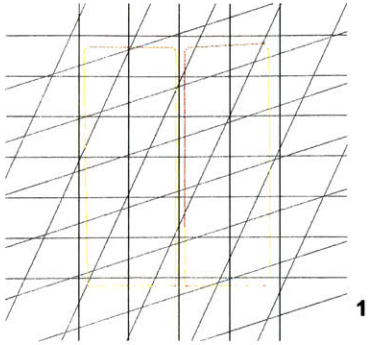


In U23

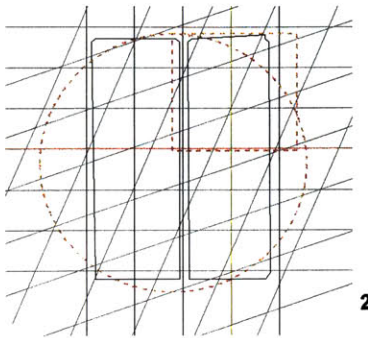
5

In U12,

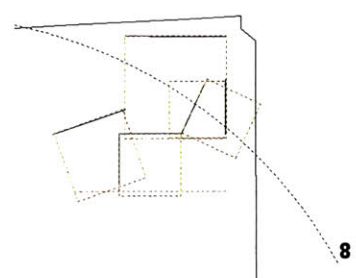
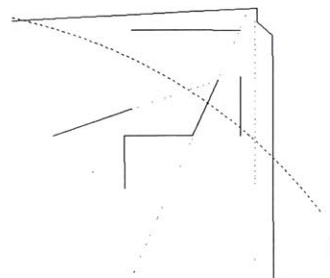
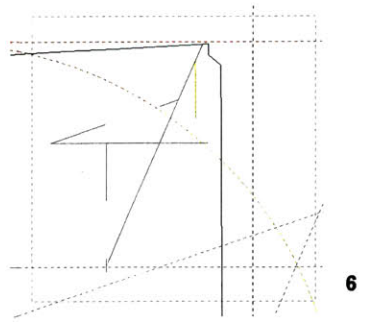
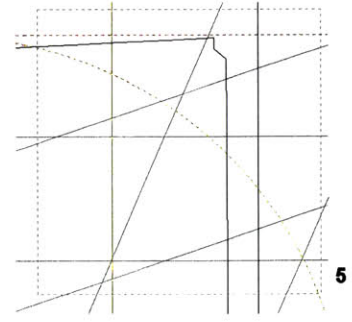
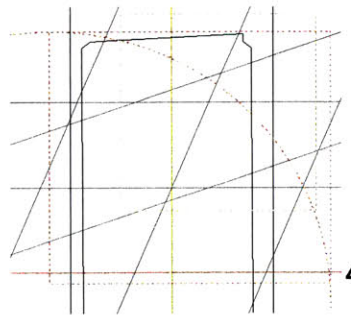
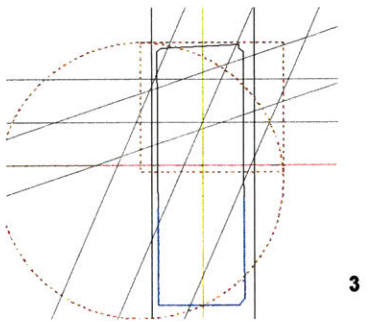
4.1.2 Site Configuration

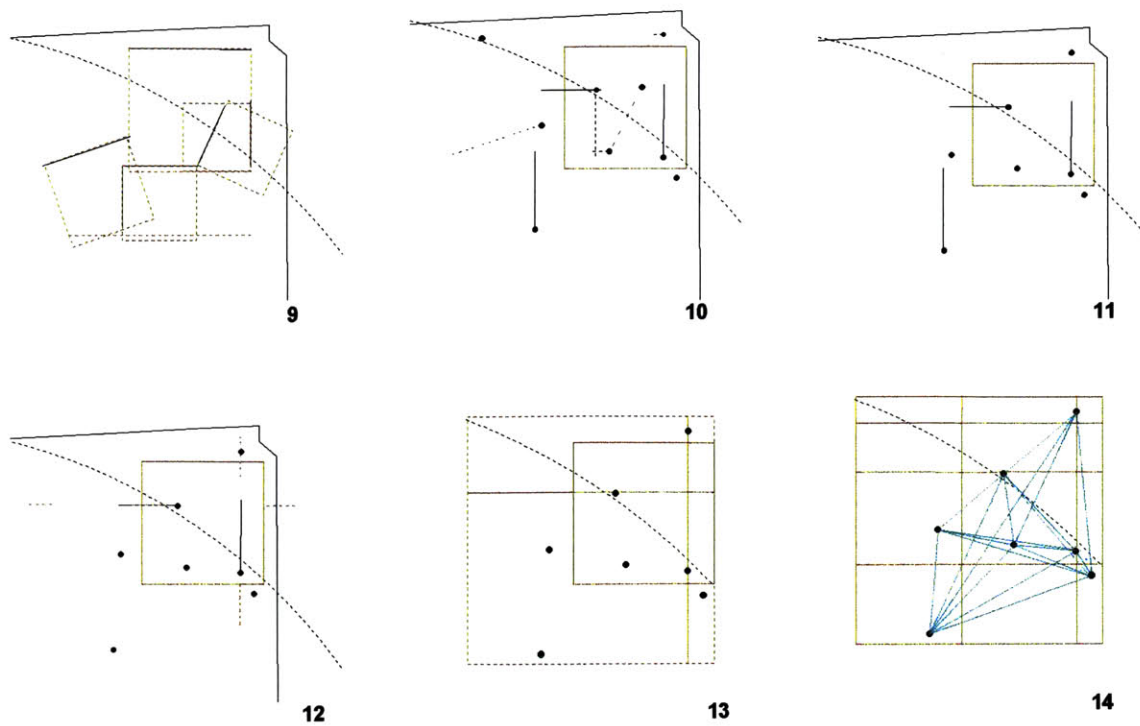


Site configuration begins with the investigation of possible geometric variations of the site. In this process, the notion of “Parti” is applied to “Making-Folly.” In Ecole des Beaux-Art, Parti is defined as the method for generating the architectural ideas. Parti means choices (from prendre parti, to make a choice, take a stand) (David Van Zanten 1976)



In U12, the line drawings have been developed to initiate the architect’s design idea.



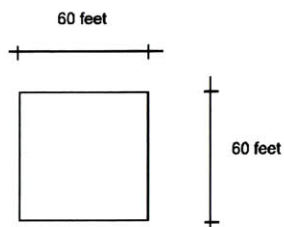


4.1.3 Site Formalization

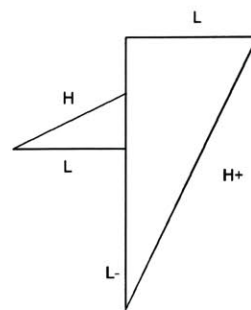
The geometric investigation provides the possible combination of direction and height. Site formalization begins with defining the basic module for the grid.

Figure 4.1.3.1 The basic module for the site grid and the initial shape

1. Basic module for Grid

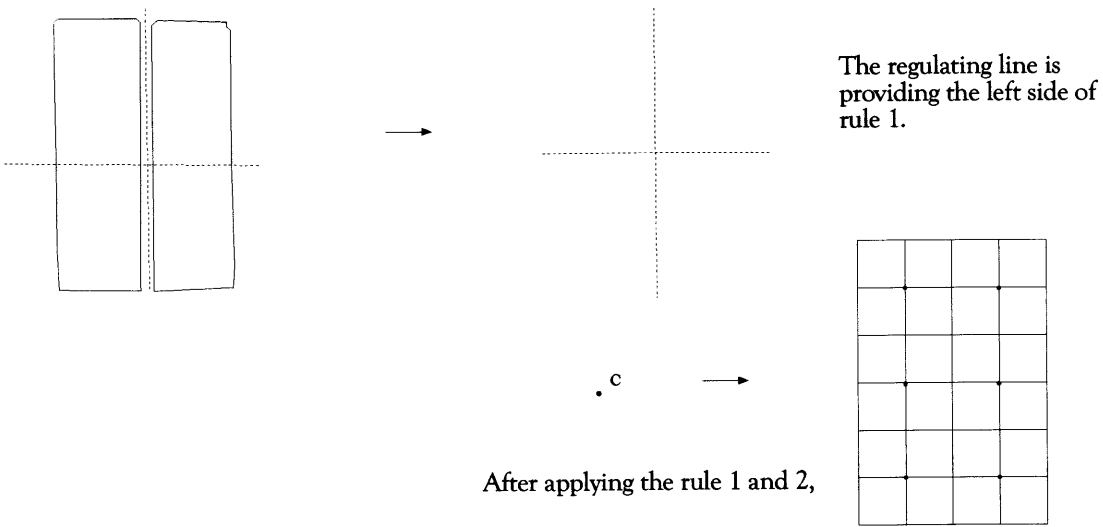
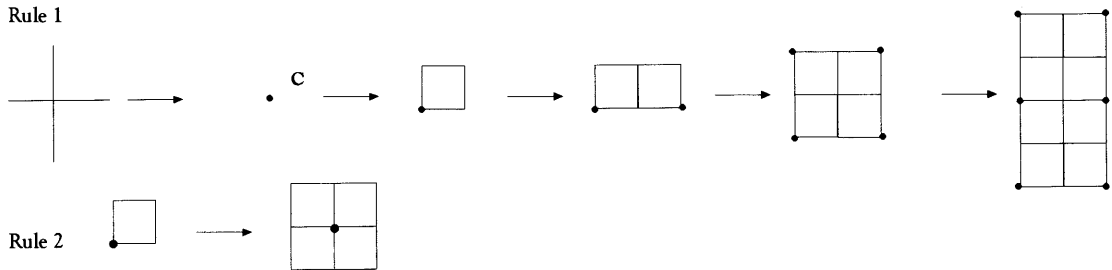


2. Initial shape containing spatial information (direction and height)

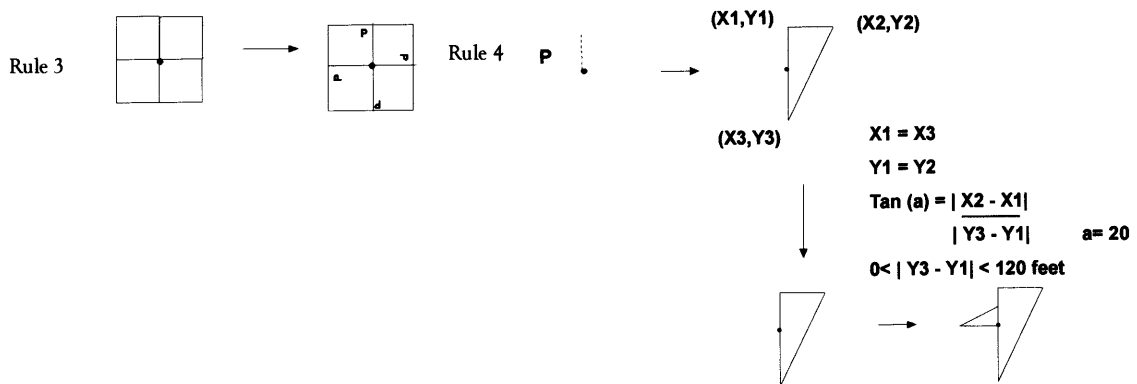


Based on the basic module and the combination, the rules for making grids are proposed in the process of formalization. Figure 4.1.3.2 shows the series of the rules for grids.

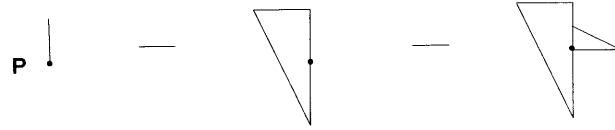
Figure 4.1.3.2



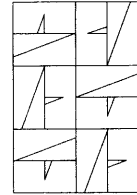
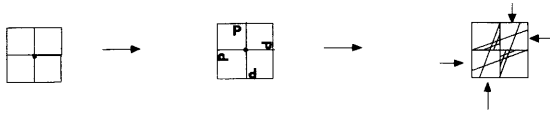
a possible site pattern is developed from the result of the combination of height and direction.



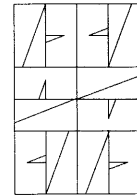
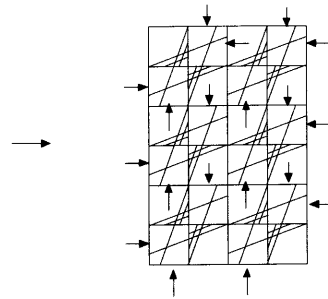
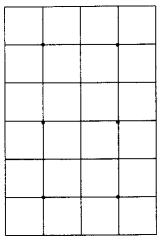
Rule 5



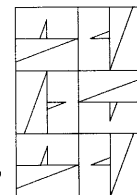
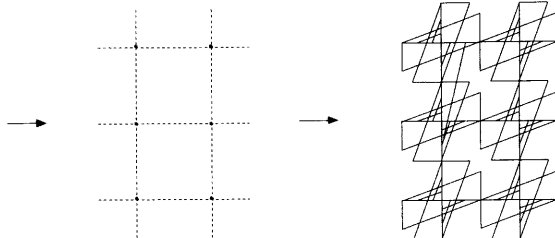
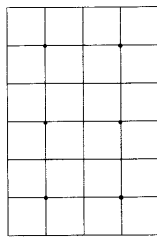
Rules 6-8 are formalized with regard to the possible direction of the entrance



Variation 1

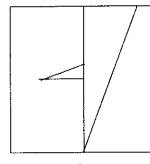
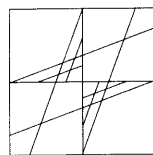


Variation 2

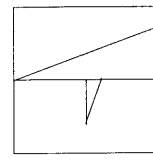


Variation 3

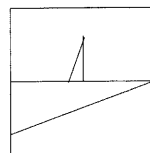
The combined basic pattern on a 60 x 60 x 4 grid



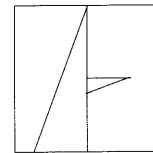
Selection 1



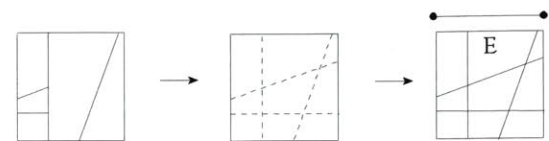
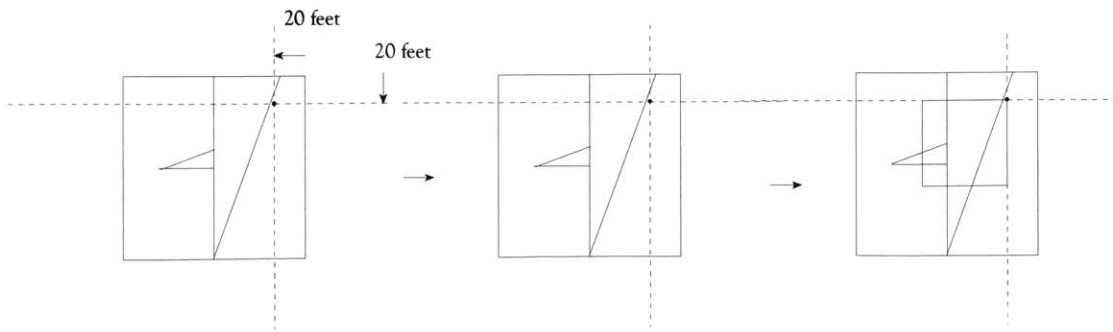
Selection 2



Selection 3

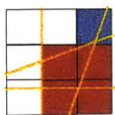
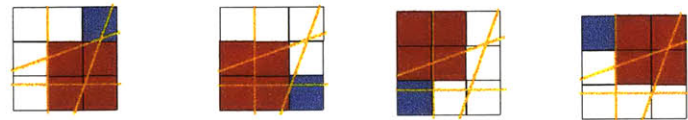
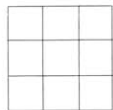


Selection 4

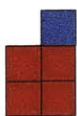
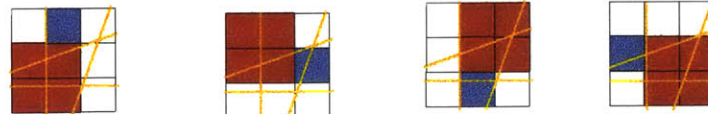


E E E E

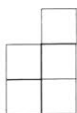
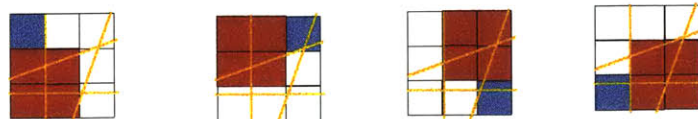
Variations based upon the direction of the entrance



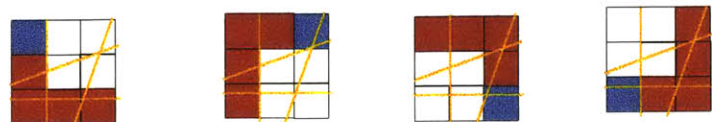
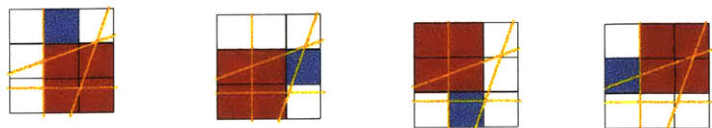
Combined Grids



Selected Grid

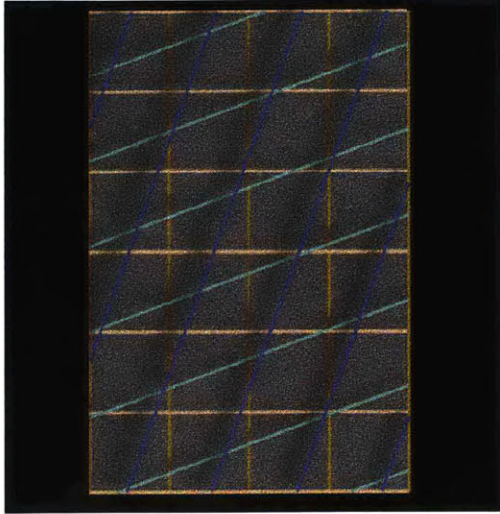


The initial territory

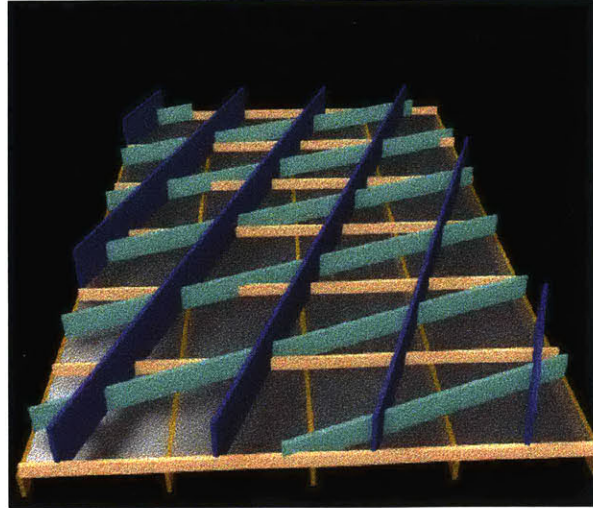


1. Site Pattern

a

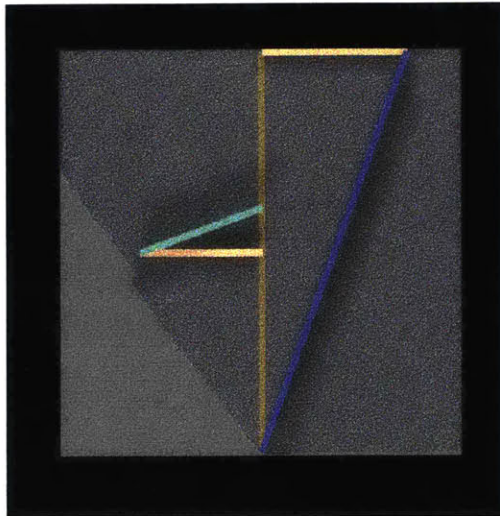


b

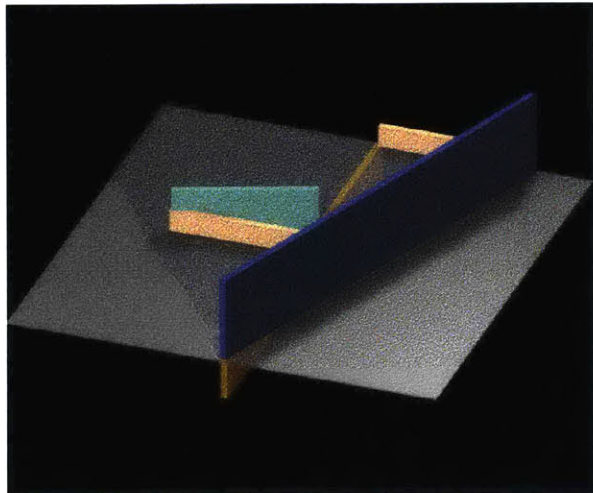


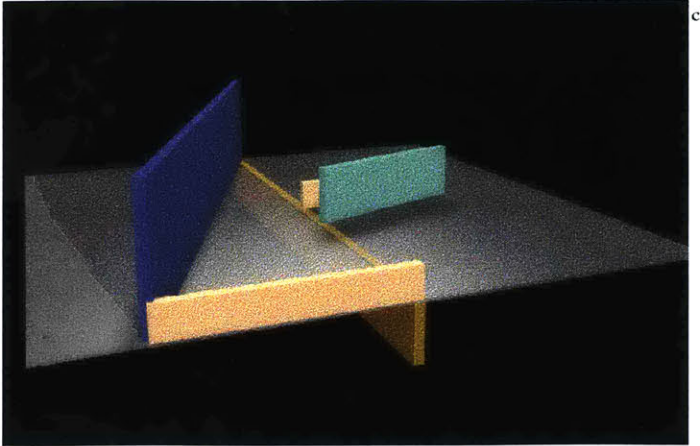
2. Initial Shape

a

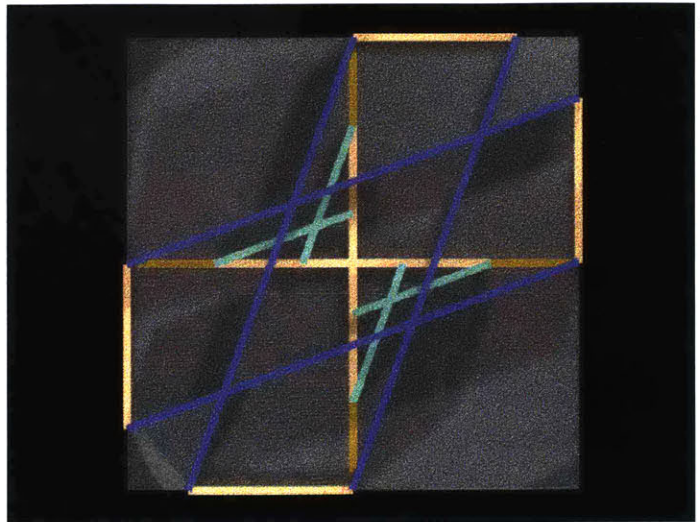


b



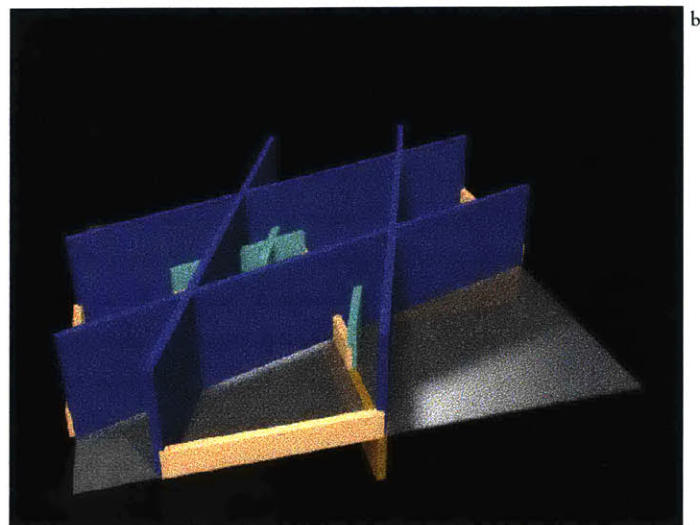


c



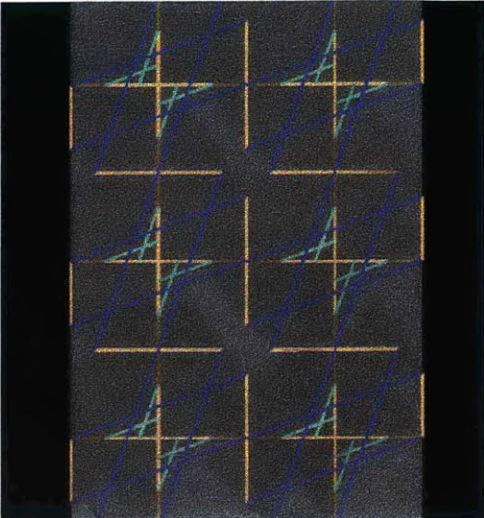
a

3. Combined shape

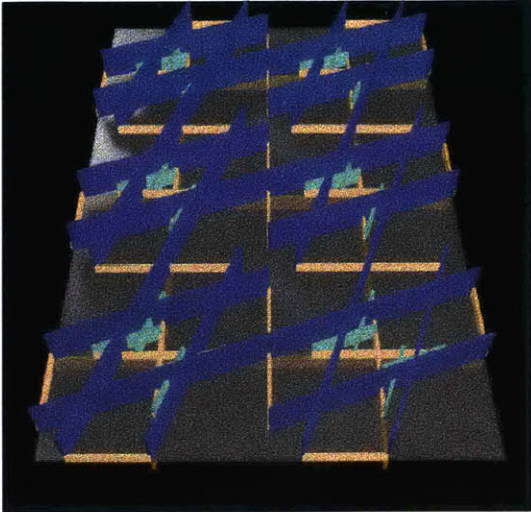


b

4. Combined shape on the formulated grid

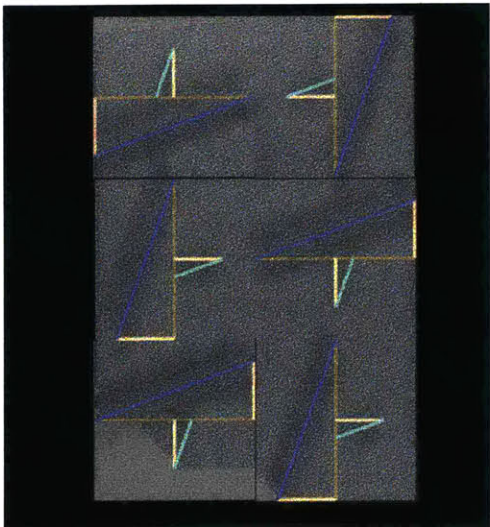


a

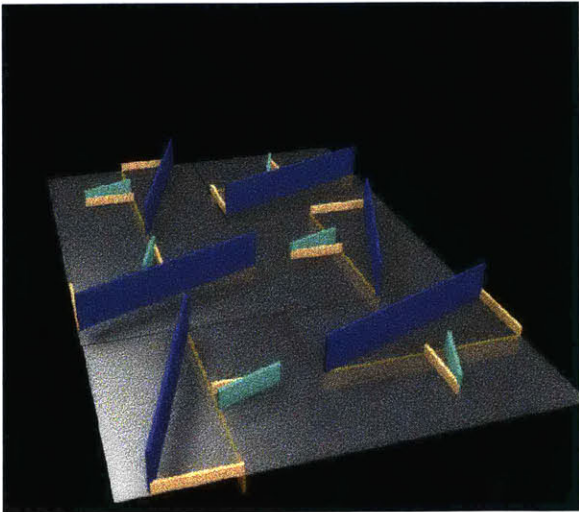


b

5. Variation I

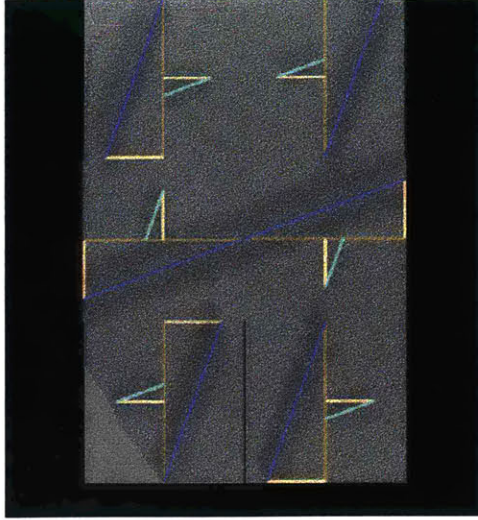


a

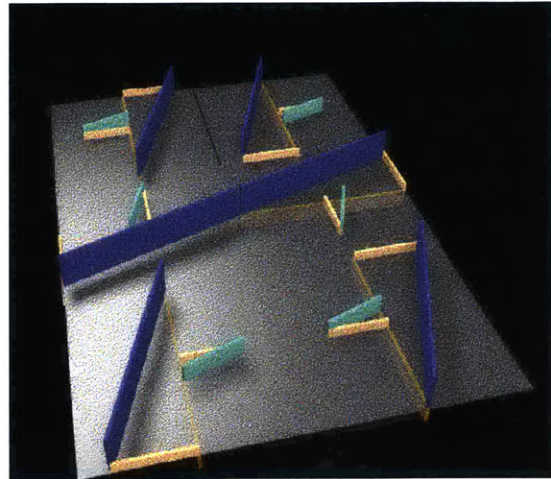


b

6. Variation II

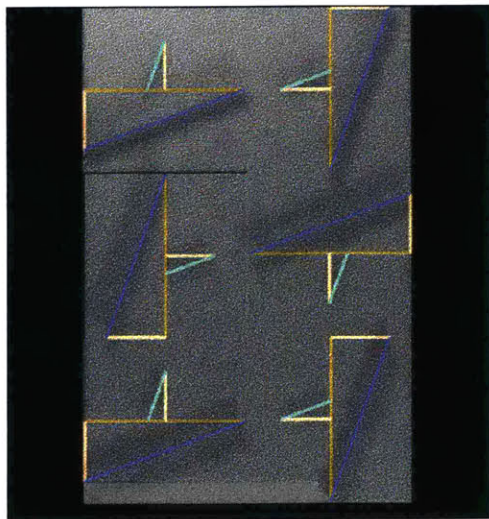


a

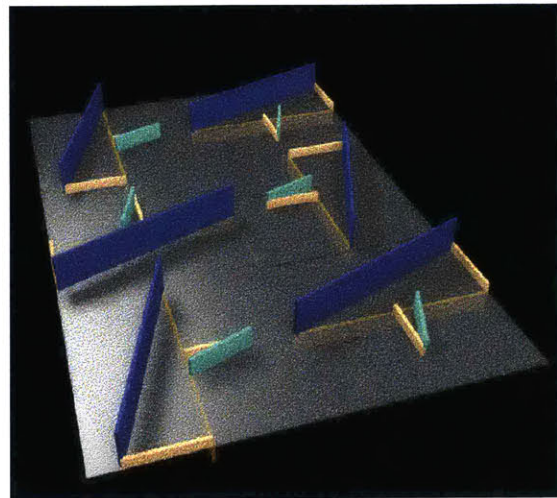


b

7. Variation III



a



b

4.2 The Spatial Grids and Units Development

The spatial grids represent the spatial partition. This means that each grid line functions in various environments such as U01, U12, U23, and U33.

Thus, each grid can be explained as follow,

In U01, each pair of points represents a line; its boundary is their entity, which is location.

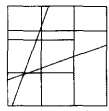
In U12, each grid line represents the direction and length.

When lines share one of their boundaries and the number of interior angles that they construct is the same as their number, they represent the plane as its boundary.

In U23, the plane represents not only the area, but also the territory.

When planes are enclosed, and share one of their boundaries, they represent the solid as its boundary.

In U33, every solid represents the space as its boundary.

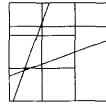


D

When the initial grid D, which is the sum of A, B, and C, is defined in U12, the spatial block of D is defined by the combination of the spatial blocks A, B, and C.



A

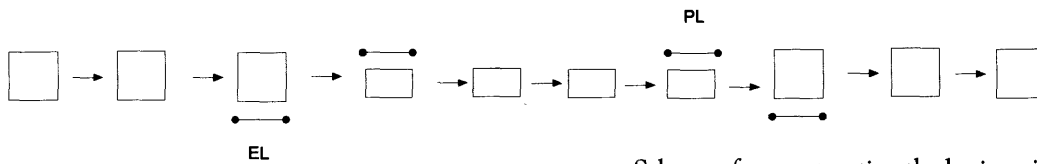


B

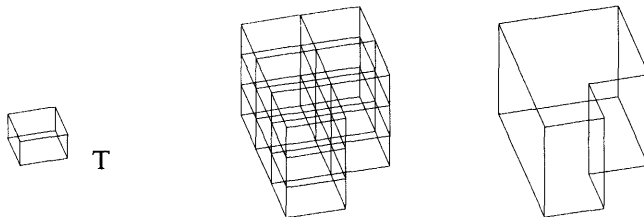


C

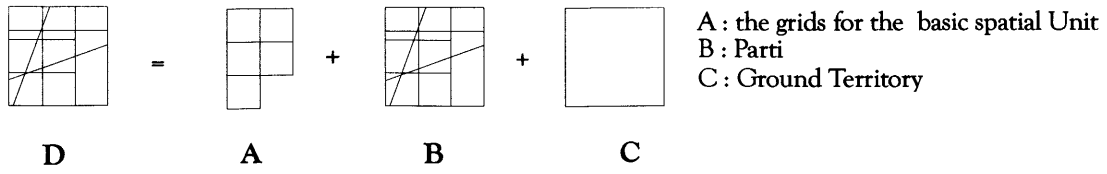
The development of the spatial block from A begins with constructing the basic unit T.



Schemas for constructing the basic unit T

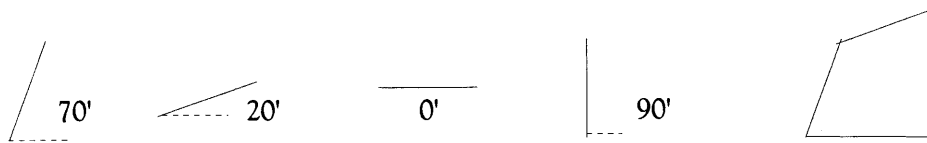


When the initial grid is defined as the sum of the A, B, and C grids,



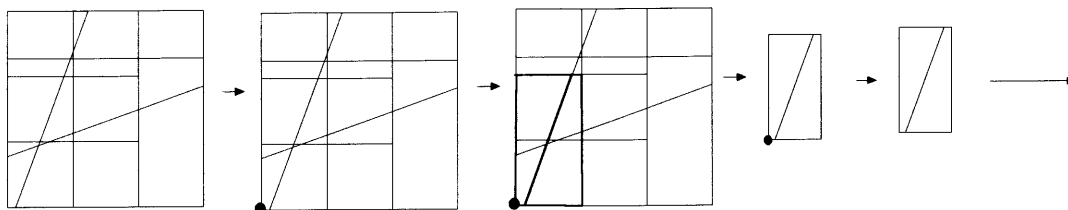
the Parti of the folly, Grid B, is developed by the architect's needs. In this case, the idea of Chinese lattice design has been manipulated to formalize Grid B. Grid B is composed of four different angles and these angles are developed by the combination of the lines (The left boundary point of each line is considered as an origin for measuring the angles).

For examples :



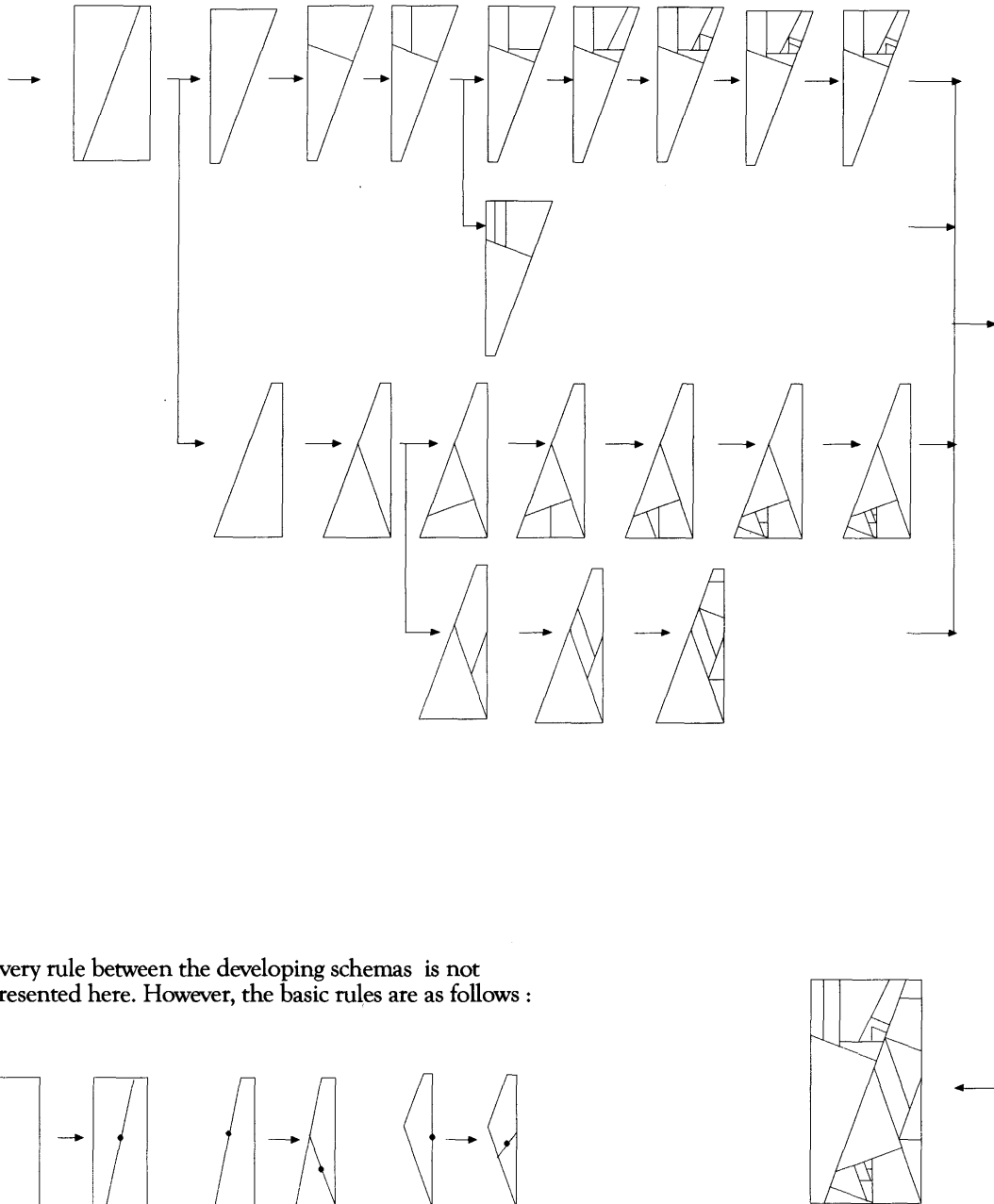
Since Grid B has the relation between these angles, the development of Grid B will be formalized in representing the relation with them.

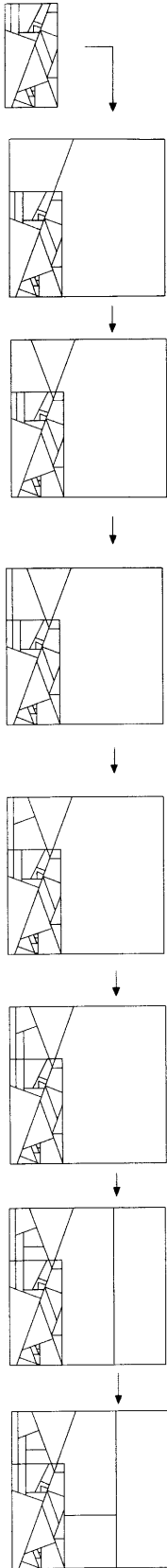
4.2.1 The Development of Grid B



CL : Chinese Lattice

4.2.2 The Schemas and Rule Application for Grid B





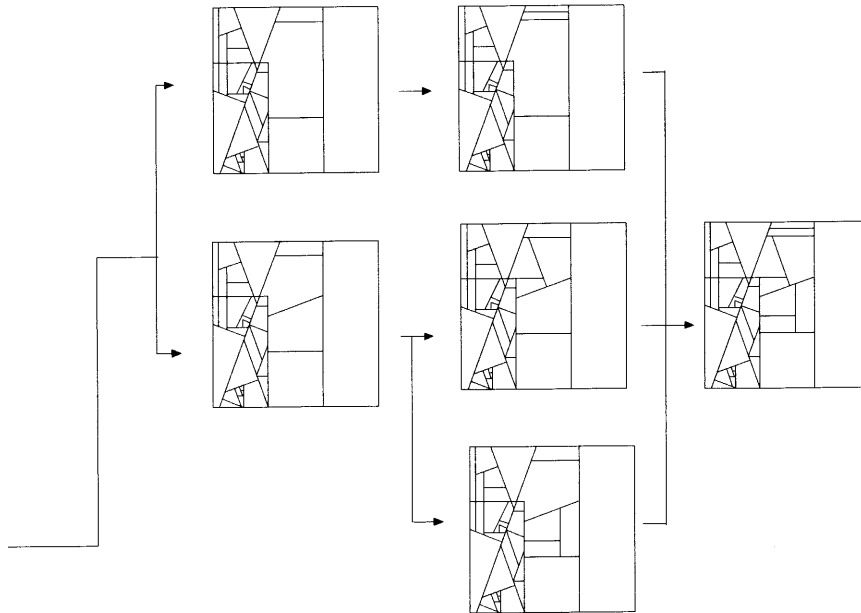
These schemas as spatial grids have been used for basic information to develop the spatial blocks.

The emergent shapes from the last schema will be applied to make each initial territory for making folly.

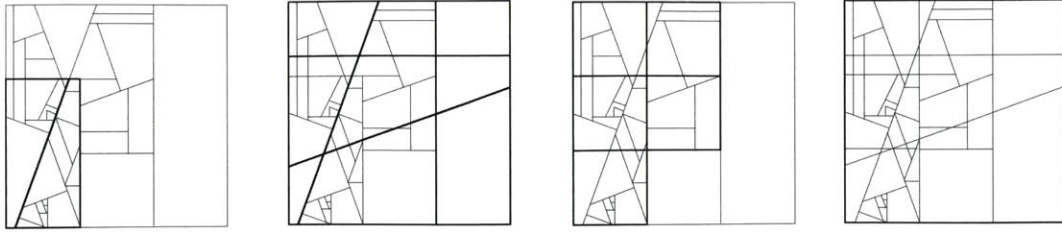
However, to define the emergent shape, Shape Grammar needs the architect's perception (the directed transformation). Thus, the architect has to compare the overall schema for its spatial organization. This means that Shape Grammar forces the architect intentionally to use the same elements in the different environments.

To do this, the architect can manipulate the boundary relations to stimulate his/her perception.

Boundary relation and territory definition were explained in the previous chapter.

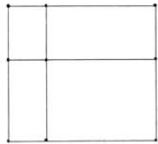


4.2.3 The Relations between Defined Grids



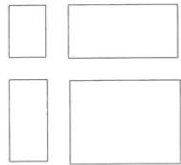
To check the possible variations of the enclosed lines as the boundary of the plane, the architect may use a mathematical application with the computational tools. For example,

U12 → U23



when nine points represent the boundary of the line in the left figure and each line is connected with taking one of the other's boundary points, four initial territories are defined.

After the architect defines the initial territories, the architect can check the possible number of enclosed planes as follows:



$$i) 4C_1 + 4C_2 + 4C_3 + 4C_4 = 15$$

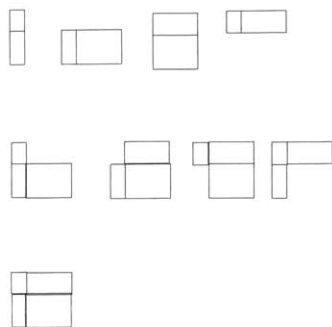
Then, the boundary relation of the plane can be applied as the constraints for deciding the proper enclosed planes.

The initial territories

In U23



The basic planes in the initial territories



The combinations of basic planes in the sharing boundary relation.

The initial planes and the sum of the initial planes, which are in the shared boundary relation, have the possibility of spatial connection. For example,

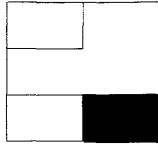


The combinations of basic planes in the discrete relation

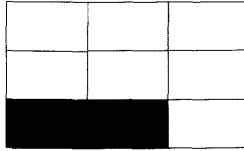
In the discrete relation, there is no spatial connection between planes.



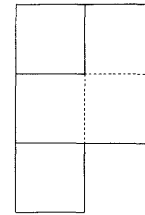
4.3 The Spatial Blocks



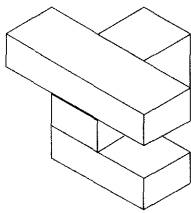
The plan for the spatial block A



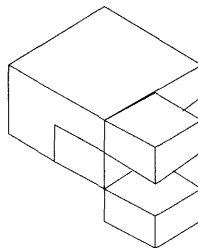
The plan for the spatial block B



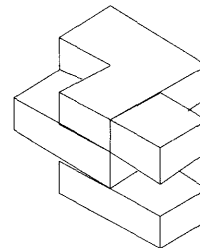
The plan for the spatial block C



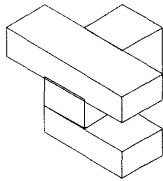
The spatial block A



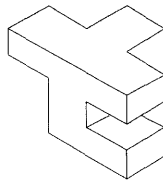
The spatial block B



The spatial block C

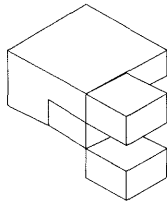


A = U {the basic units}

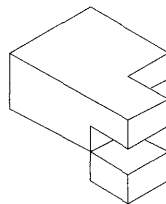


A = + {the basic units}

After the spatial grids are defined, the possible combinations of the spatial blocks are explored.

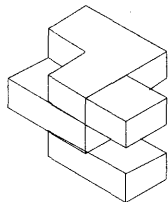


B = U {the basic units}

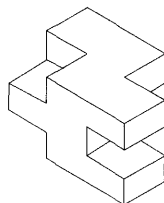


B = + {the basic units}

From the different pictorial points, each spatial block is developed.

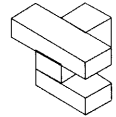
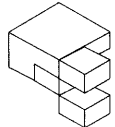
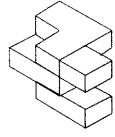
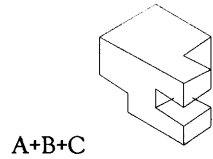


C = U {the basic units}

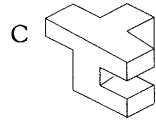
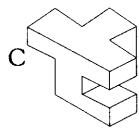
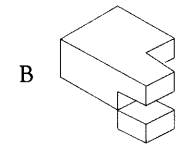
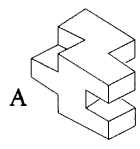
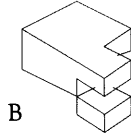
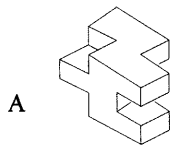
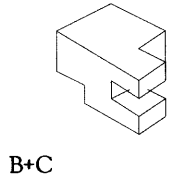
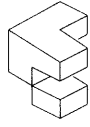


C = + {the basic units}

The manipulation of the spatial blocks with different operations such as sum(+) and product(.)



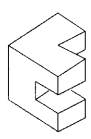
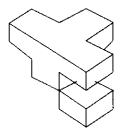
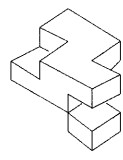
+ Sum
. Product



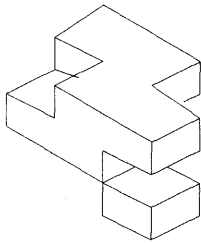
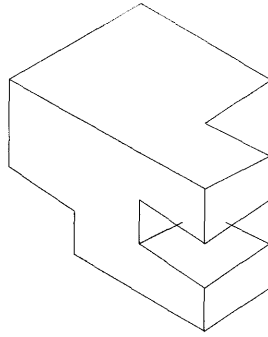
A.B

B.C

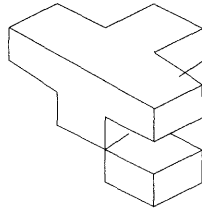
A.C



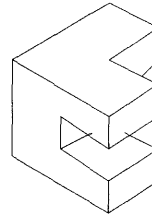
The Sum of $\{A+B\}$, $\{B+C\}$, and $\{C+A\}$



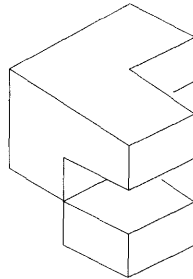
$A+B$



$B+C$

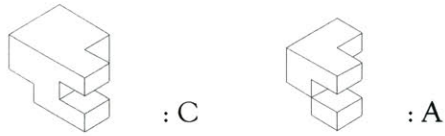


$C+A$

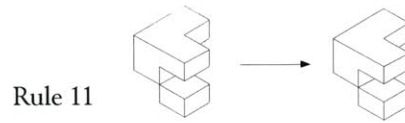
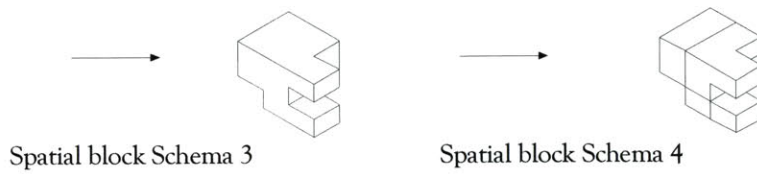
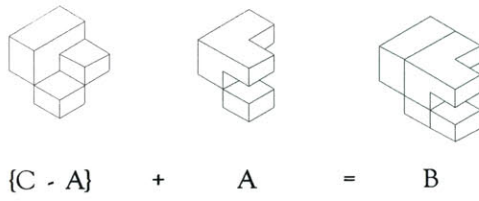


The Product of $\{A+B\}$, $\{B+C\}$, and $\{C+A\}$

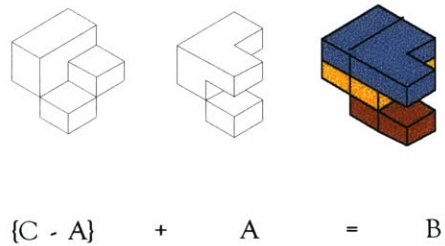
4.3.1 The Operations for Spatial Blocks



When C is the sum of the variations of the defined spatial blocks and A is the product of them, the basic spatial block B for folly is defined as $\{C - A\} + A$.



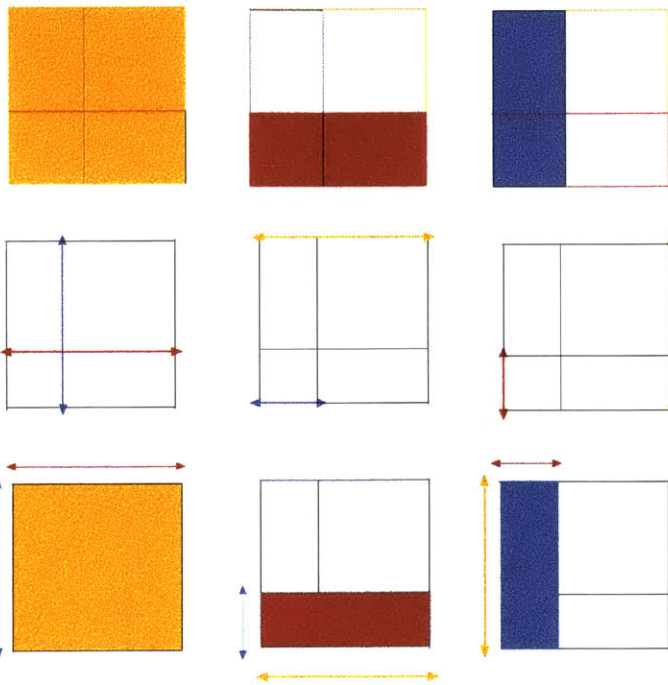
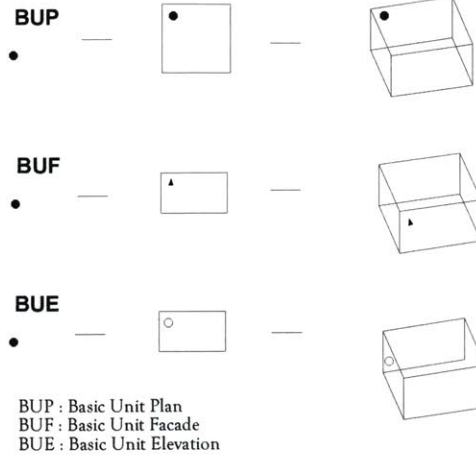
In U33,



We already defined the basic spatial block as the left figure indicates.

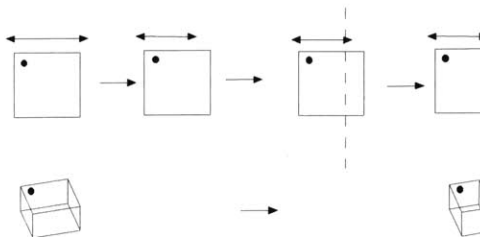
From the aspect of spatial relations, the spatial block can be divided into the blue, yellow, and red parts. Each set of colored blocks will represent the possible spatial layers in the folly.

4.3.2 The Schemas for controlling the basic spatial unit



When the basic unit is defined by the controlling schemas, the basic unit can be controlled as in the diagram to the right

Examples:



After the result of this data abstraction is compared to already defined grids, several meaning categories for "Making-Folly" are formalized.

4.4 The methods of formalizing various meaning categories.

Dijyw : when the basic elements are represented with the spatial definition, the elements are described
 Dijyw. In Dijyw, i means the domain of the basic elements, j the environment of i, y the categories of the spatial definitions and w means the items in the categories
 ((0 <= i, j <= 3), (1 <= y <= n, for "making-folly", n= depends on the user's need) (1 <= w <= n)).

Dijyw = Uij x Sijyw, when **Sijyw = Uij x My x Iw**
My means the defined category including the defined items
Iw means the specific number of items in the category
Sijyw means the symbols represented in Uij that pertain to the specific item w in category y

The algebra based upon the spatial definition
 : **Pijyw = Uij x S33yw**, when **S33yw = U33 x My x Iw**
 (here, since y is restricted to the one category of the spatial definition that I will make, I will represent Pijyw as Pijw)

The algebra based upon the structure
 : **Tijyw = Uij x S33yw**, when **S33yw = U33 x My x Iw**
 (here, My is restricted to the Structural knowledge that I have)

The algebra based upon the color
 : **Cijyw = Uij x S23yw**, when **S23yw = U23 x My x Iw**,
 (here, since y will be restricted to the one category that I will make, I will represent Cijyw as Cijw)

4.4.1 The Spatial Definitions for "Making-Folly"

1. The enclosed space :when the space is enclosed by the solids, the space is defined as the enclosed space
2. The open space : when the space is not enclosed by the solids, the space is defined as the open space.
3. The enclosed plane : when the solid encloses the space or it is inside the enclosed space, the boundary of the solid is defined as the enclosed plane.
4. The open plane: when the solid is in the open space, the boundary of the solid is defined as the open plane.
5. The connector: when the enclosed space creates an overlapping relation between more than two enclosed spaces by engaging itself in the sum procedure between them, it is defined as the connector.
6. The connector plane : when the solids are the boundary of the connector, the boundary of the solid is defined as the connector plane.
7. The connection : when the enclosed spaces are transformed into an overlapping relation by the connector, the process of the transformation is defined as the connection. when the boundary of enclosed spaces in the connection are defined A, B, and the boundary of the connector as C,





$$\text{The connection} = \{A - C\} + \{C - A\} + \{C - B\} + \{B - C\}$$

7. The opening : the opening is part of the connection, when the connection is defined as above.

$$\text{The opening} = \{A - C\} \text{ and } \{B - C\}$$

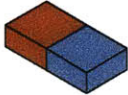

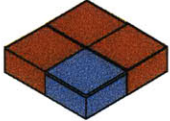
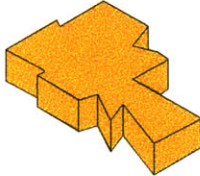
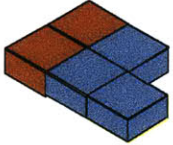
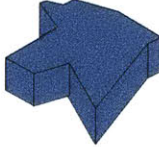
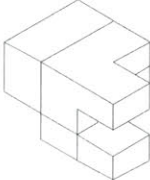
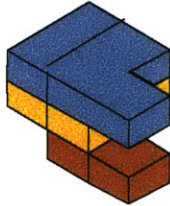
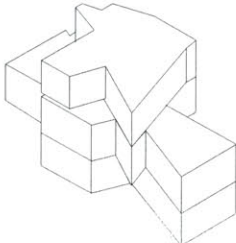
8. The circulation: the circulation can be defined by the openings and connectors between the enclosed space
9. The void : when the connector doesn't define the circulation, it is defined as the void.
10. The solid: it has already been defined in chapter 2.
11. The space plane: when the empty shape is defined as the boundary of the space, the boundary of the space is defined as the space plane.

4.4.2 The Color Definitions for "Making-Folly"

-  This color of the left shape is defined as 1
-  This color of the left shape is defined as 2
-  This color of the left shape is defined as 3
-  This color of the left shape is defined as 4

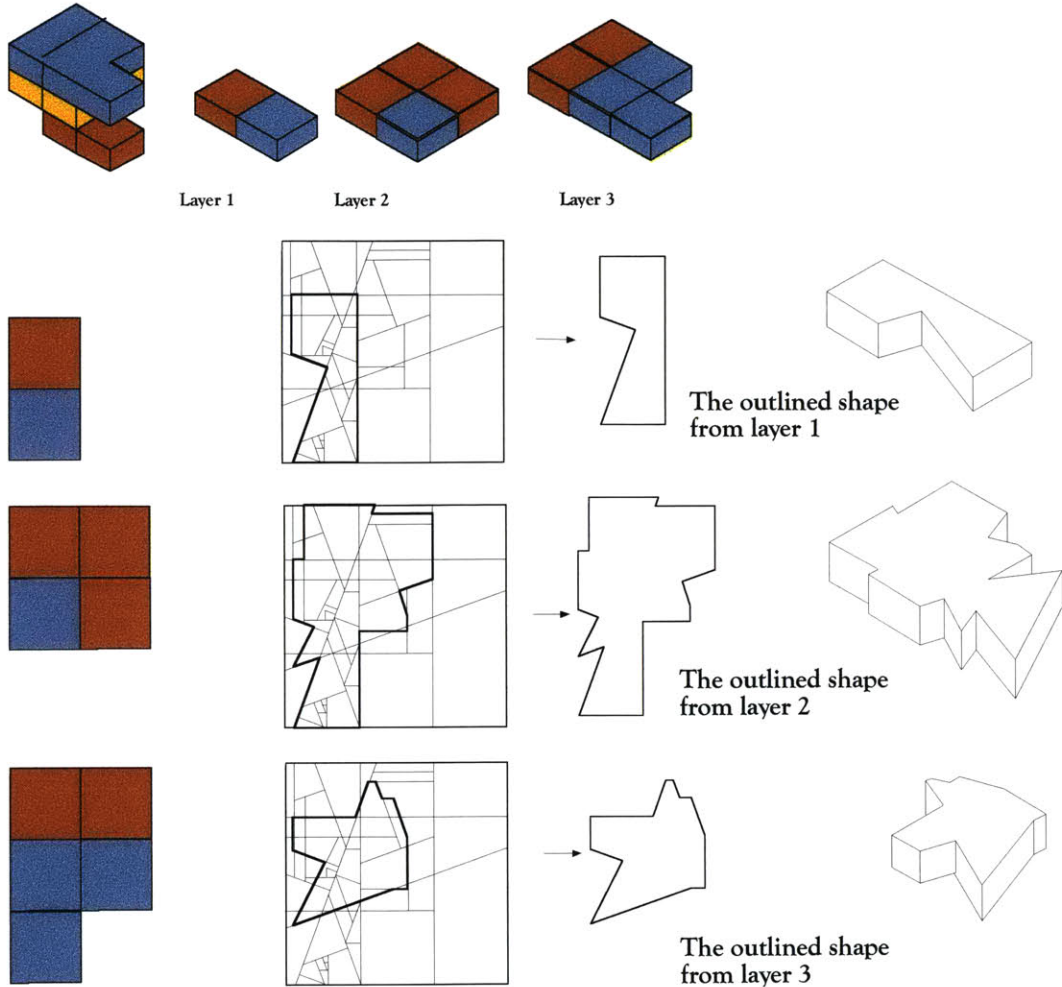
4.4.3 The Layer Definitions for "Making-Folly"

Now, I will define the layers, based upon their heights as follows:

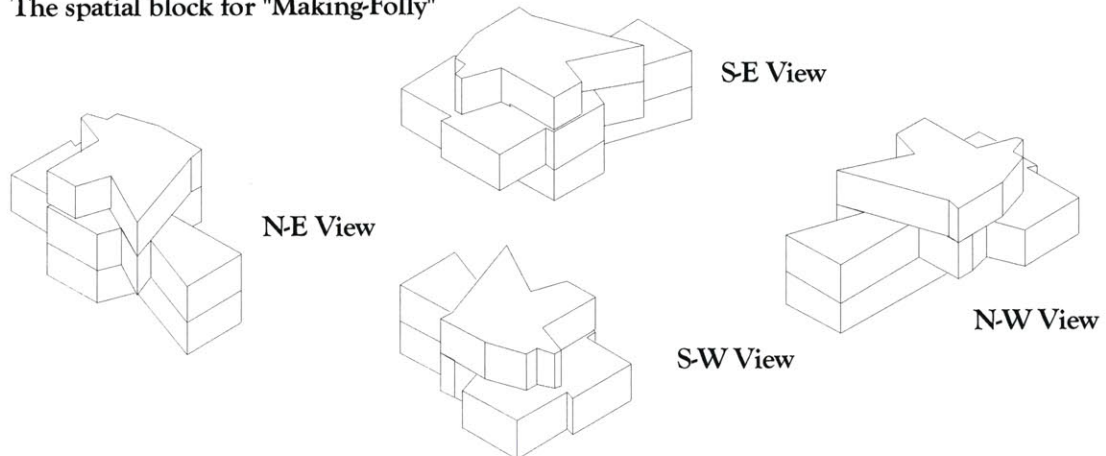
	Layer 1 : When the spatial blocks are 9.0 feet in height in the spatial grid, the set of spatial blocks is defined as layer 1.		In L33lx C331
	Layer 2 : When the spatial blocks are 10.3 feet in height and they are in layer 1 of the spatial grid , the set of spatial blocks is defined as layer 2		In L332x C332
	Layer 3 : When the spatial blocks are 9.8 feet in height and they are in the layer 2 of the spatial grid, the set of spatial blocks are defined as layer 3.		In L333x C333
			In L33w x C33w
			In U33

After several meaning categories are established in "Making-Folly," the manipulation of the defined spatial blocks can be developed in the combined algebra.

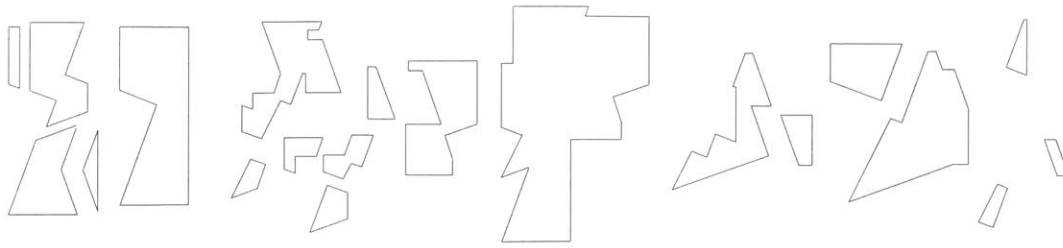
4.4.4 The representation of the spatial blocks with the layer definition.



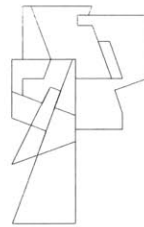
The spatial block for "Making-Folly"



4.5 The Initial Territories



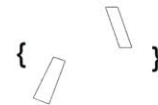
The initial territories
with the layer & color
definitions



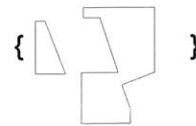
I. The enclosed plane :



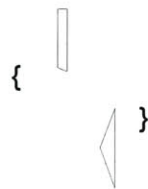
II. The connector plane :



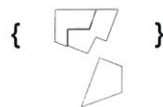
III. The open plane :



IV. The solid plane :



V. The void plane :

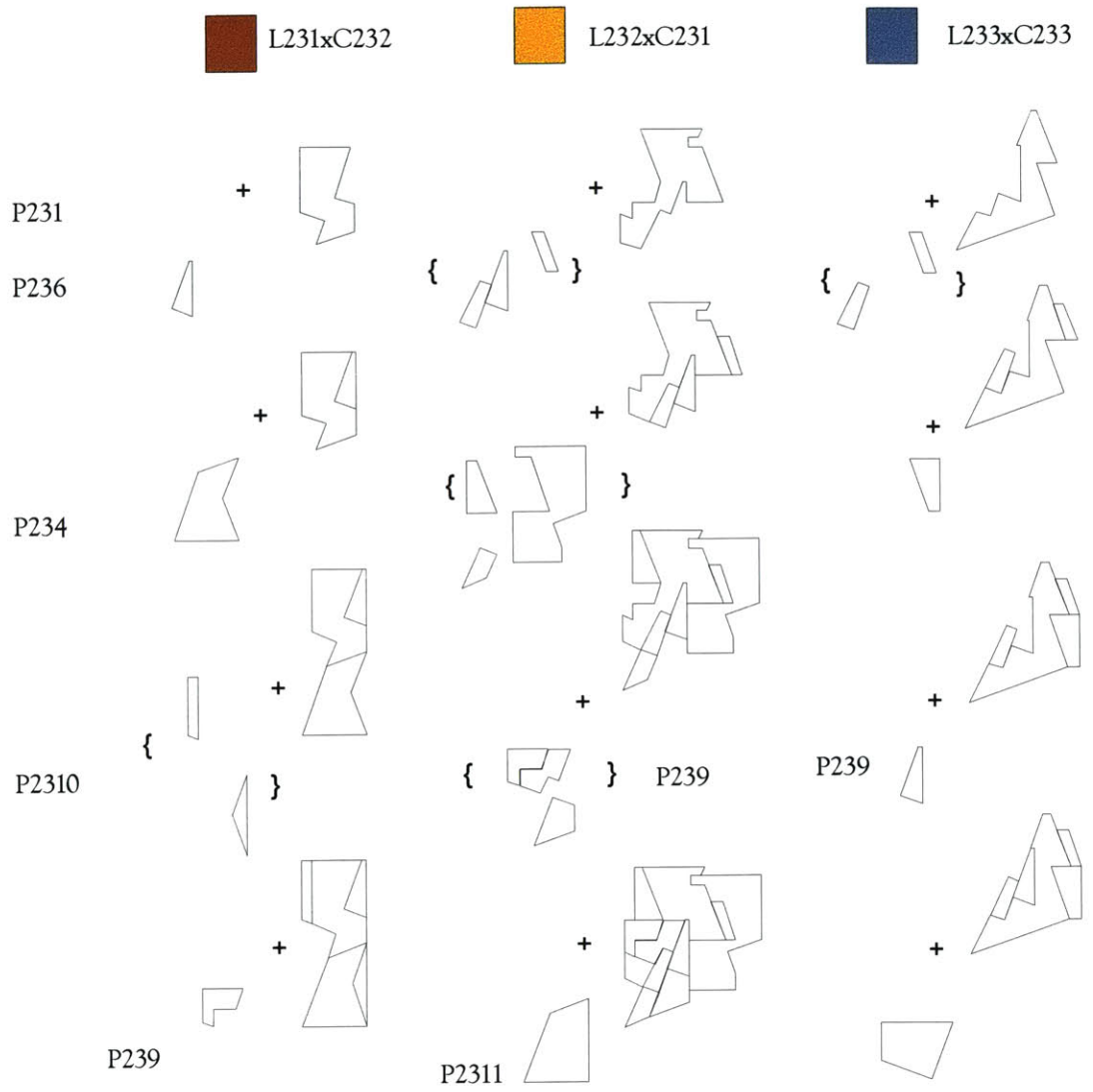


VI. The space plane :

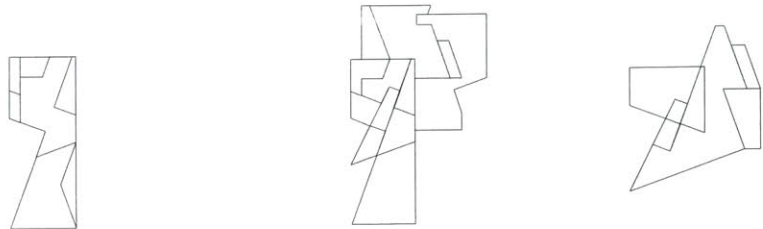


In U23,

after the initial territories are defined in the spatial grids, each data abstracted shape is manipulated by the architect's own combination of the different meaning categories.

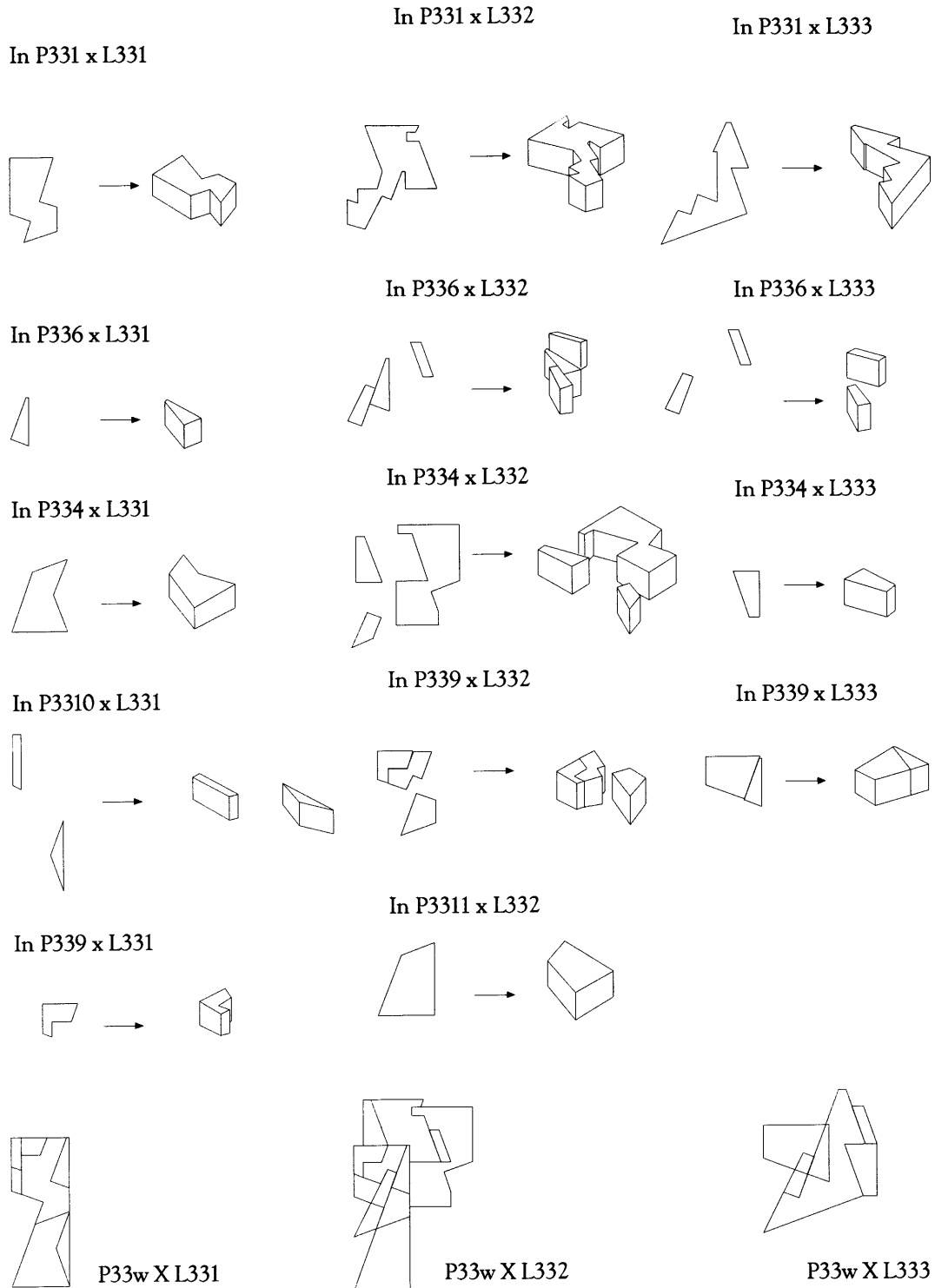


The void plane is described as U12 although it is a plane

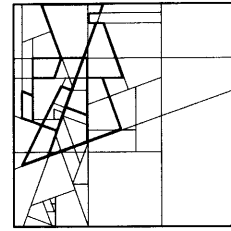
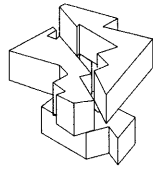
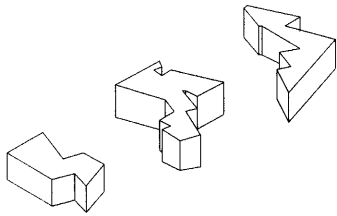


4.5.1 The development of the initial territories based upon the algebra

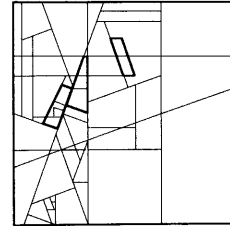
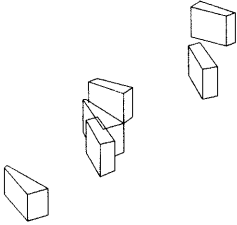
In this process, the initial territories have different meanings as the spatial components.



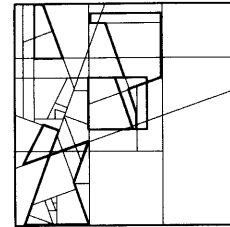
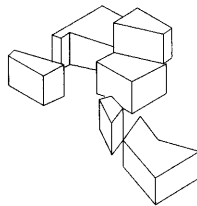
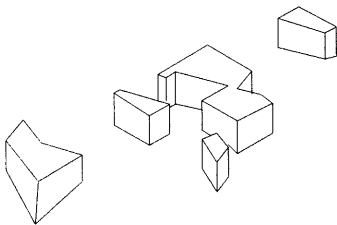
In P331 x L331xL332xL333



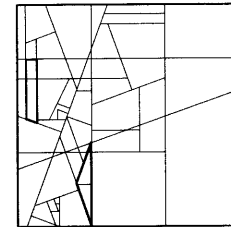
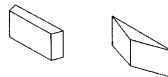
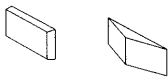
In P336 x L331xL332xL333



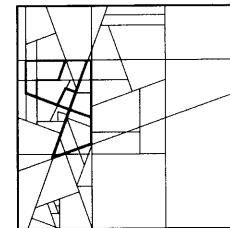
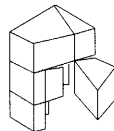
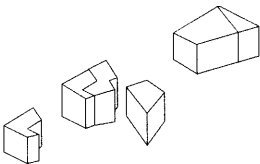
In P334 x L331xL332xL333



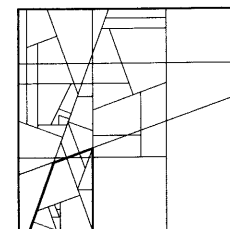
In P3310 x L331xL332xL333



In P339 x L331xL332xL333

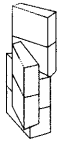



In P3311 x L331xL332xL333




After the folly is divided into the spatial components, each component has its own spatial meaning categories. Thus, the architect can develop its design in detail with these components.

4.5.2 The Spatial Components Development between U12 and U33 with different Algebra



In $P336 \times L331 \times L332 \times L333$, when the combination is defined as $P334 \times L331 \times L332$, it is described as , and it means the connector between layers 1 and 2.

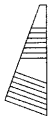
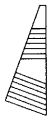
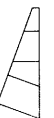


In $P336 \times L331 \times L332$, $P336 \times L331$ is defined as 

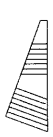
In U33,



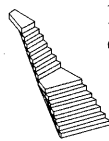
In U12



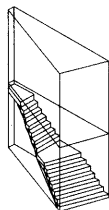
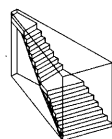
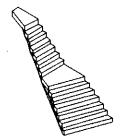
After design development proceeds in U12, the result is used for the spatial grids of $P336 \times L331$. Therefore, a detailed design can be achieved by the manipulation of the defined algebras.



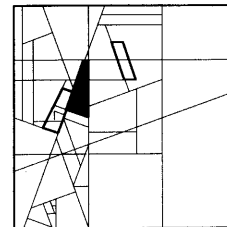
In U23, when the figure at left is defined as the set of several planes, a plane can be defined as one of the spatial definitions. In this case, each planes is defined as the solid $P3310$.



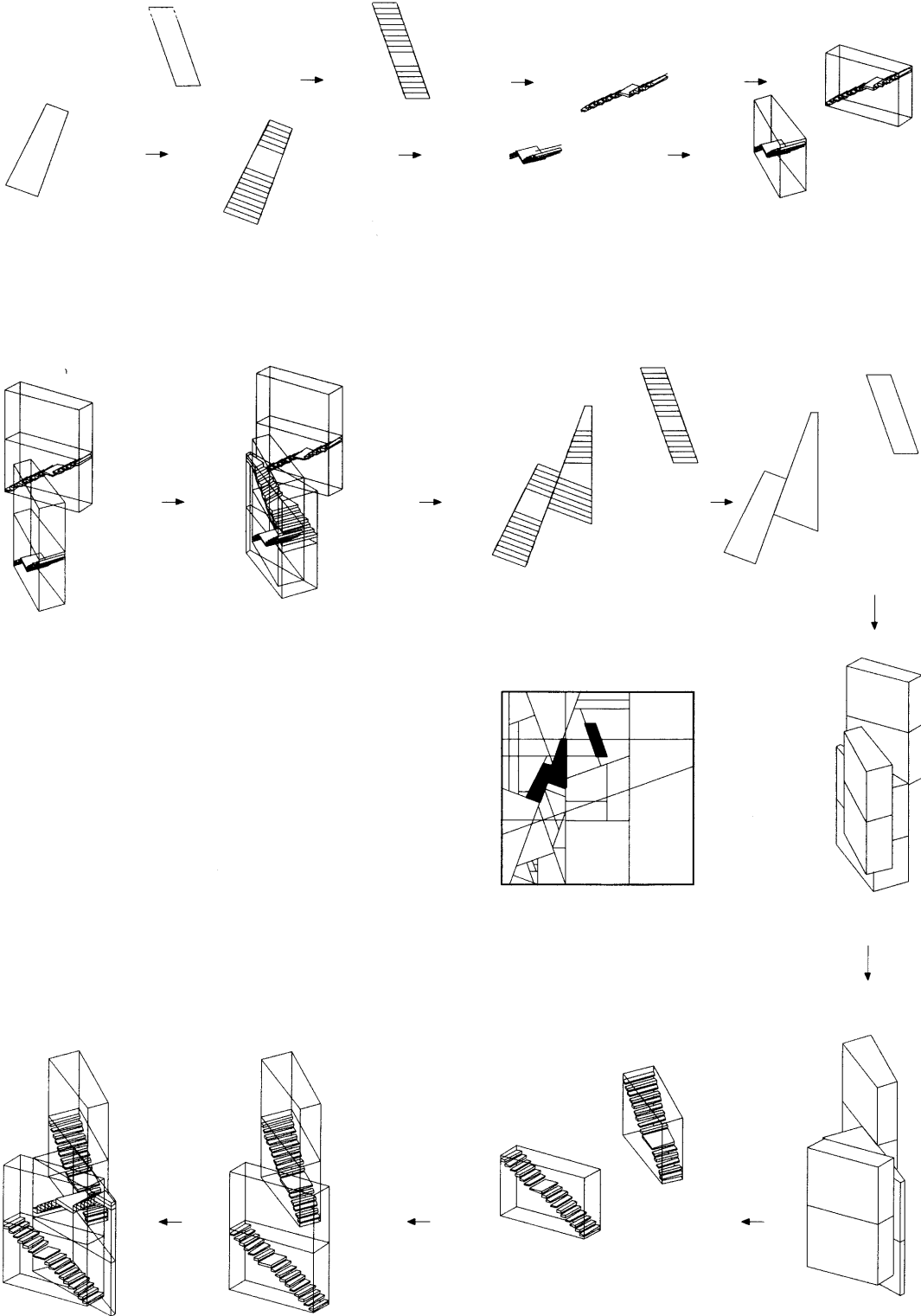
By creating the definition of the layers between the solids, we can get the combination of algebras as $P3310 \times L33yw$



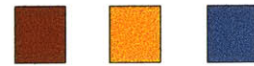
After the combination of algebras is developed in the small spatial block, it is defined in the larger block based upon the spatial grids and initial territories.



The other connectors can be defined by the same method, and then they are combined in the data abstracted spatial block based upon the grids.

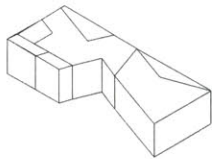


4.6 The spatial components design with Pijw x Lijw

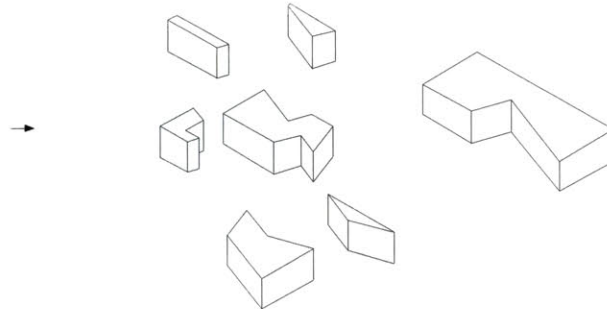


Since the layers are defined as the sets of spatial blocks, sets of spatial blocks can be developed with the spatial and layer definition.

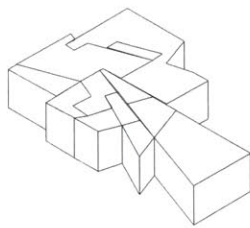
P33w x L331



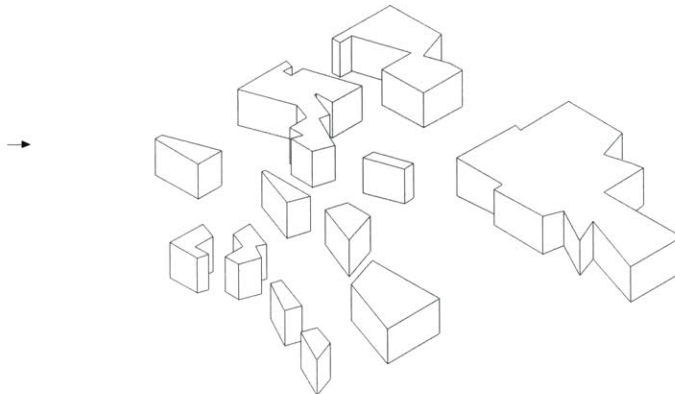
U33



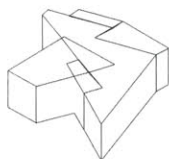
P33w x L332



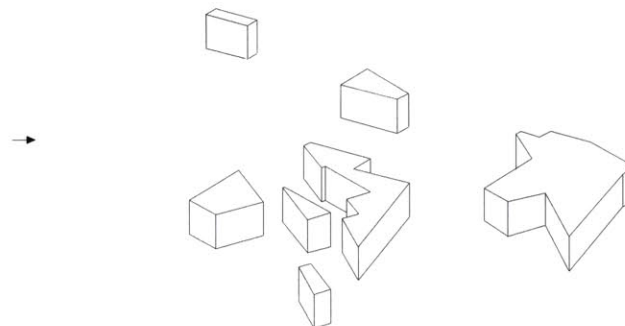
U33



P33w x L333



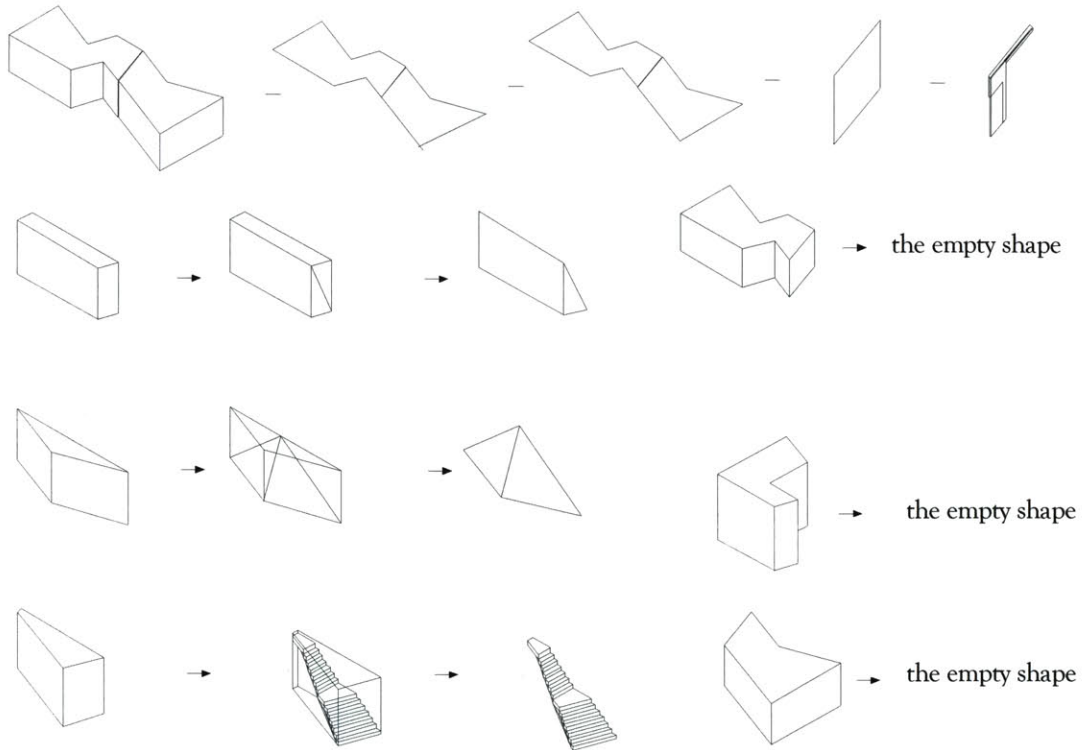
U33



After the design developments begin in U33, the result of the development is transferred to the combination of the different algebras, as in P33w XL33w or the combination of the new defined meaning categories.

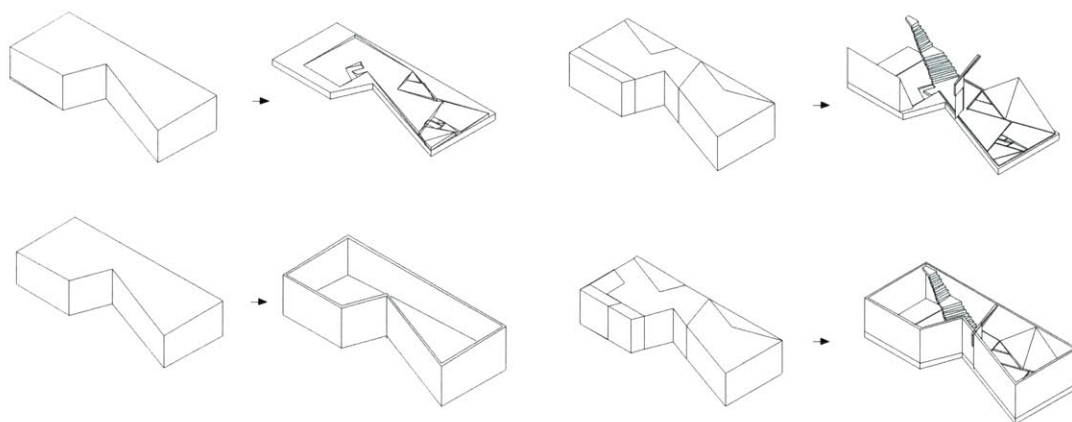


4.6.1 P33w X L331



The development in the spatial block

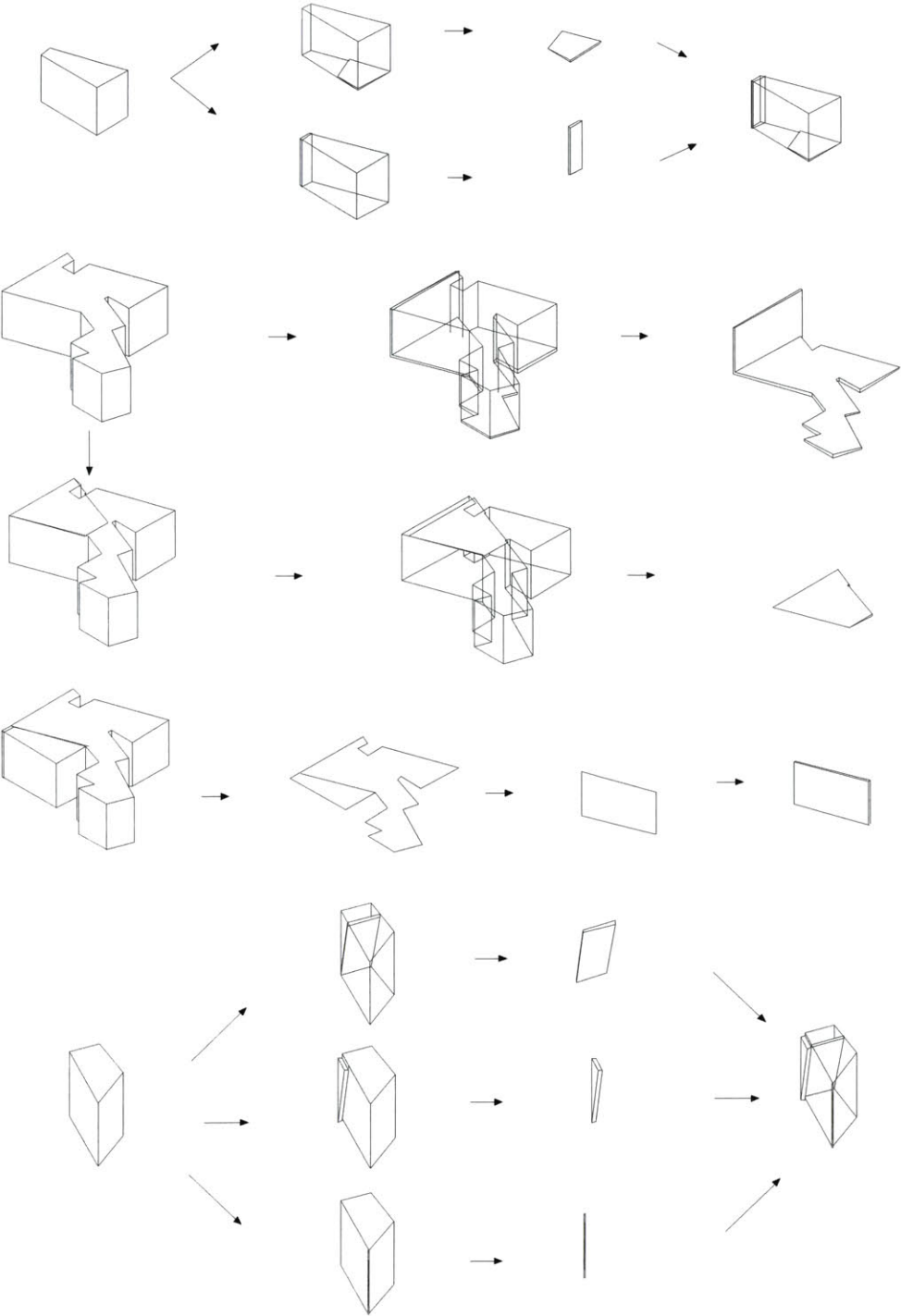
The combination of the different spatial blocks

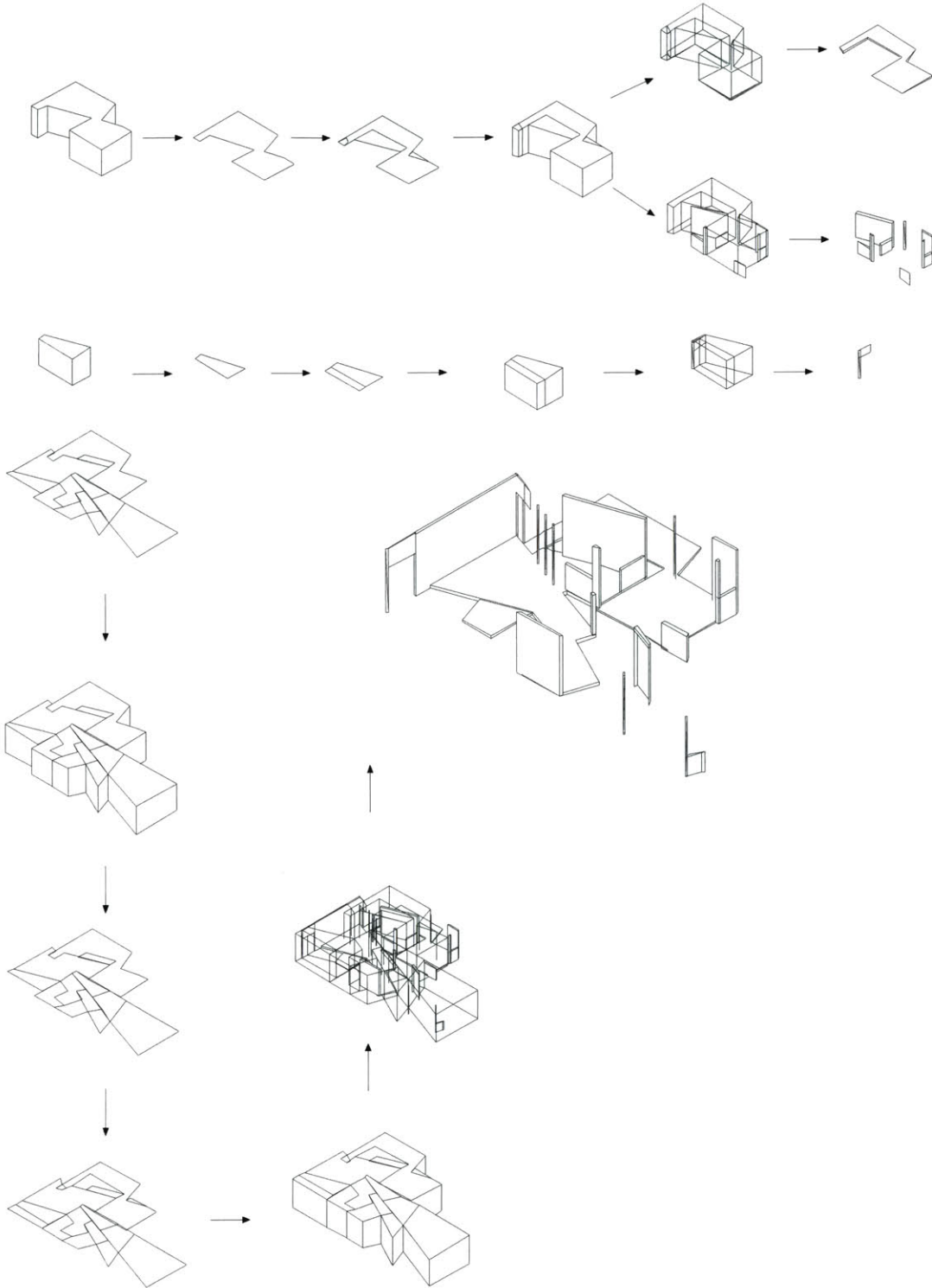


In U33, each spatial block can have its own categories depending on the architect's needs. The design development of the spatial blocks is performed by the same method as for the initial spatial block development.



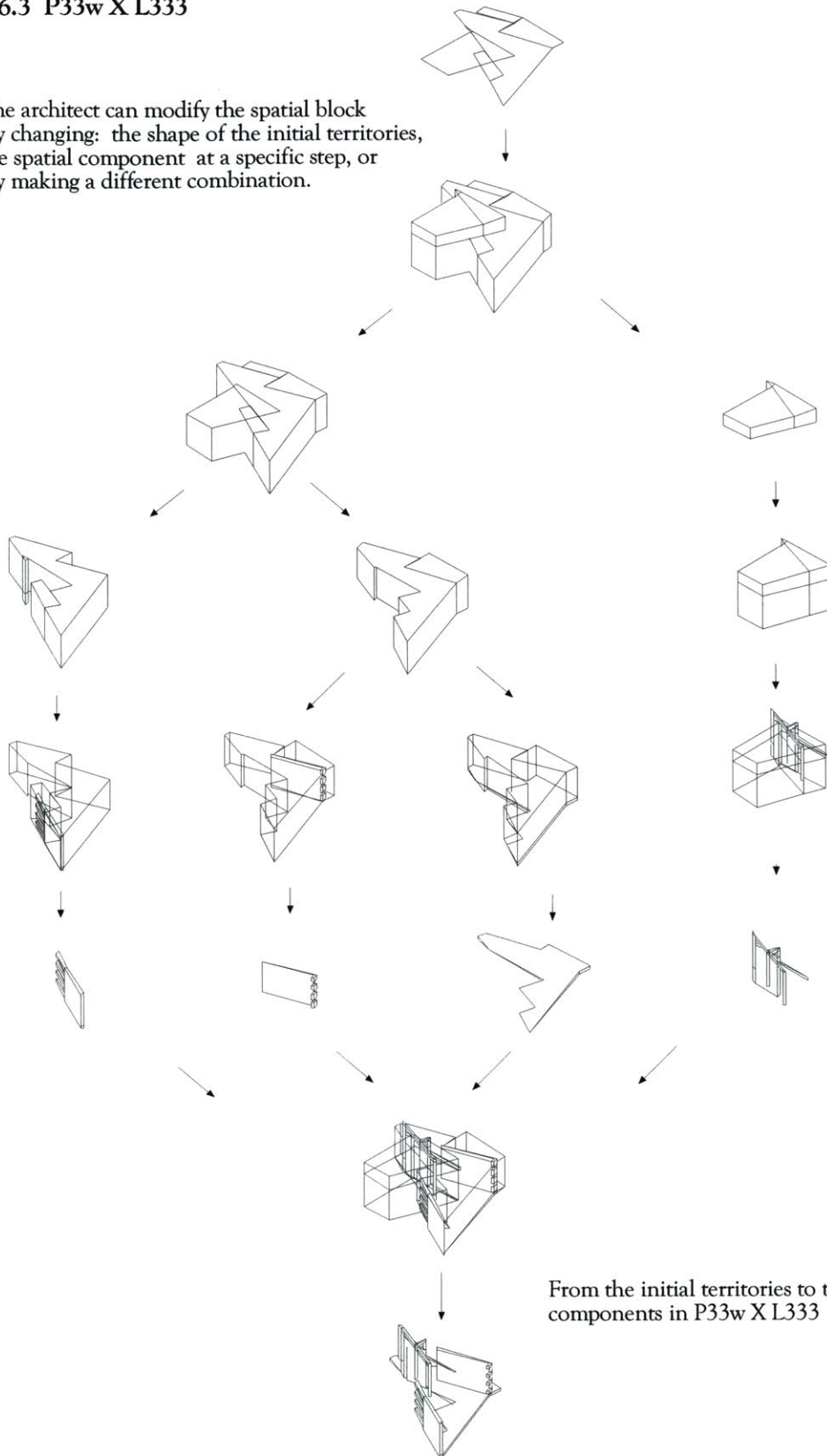
4.6.2 P33w X L332





4.6.3 P33w X L333

The architect can modify the spatial block by changing: the shape of the initial territories, the spatial component at a specific step, or by making a different combination.



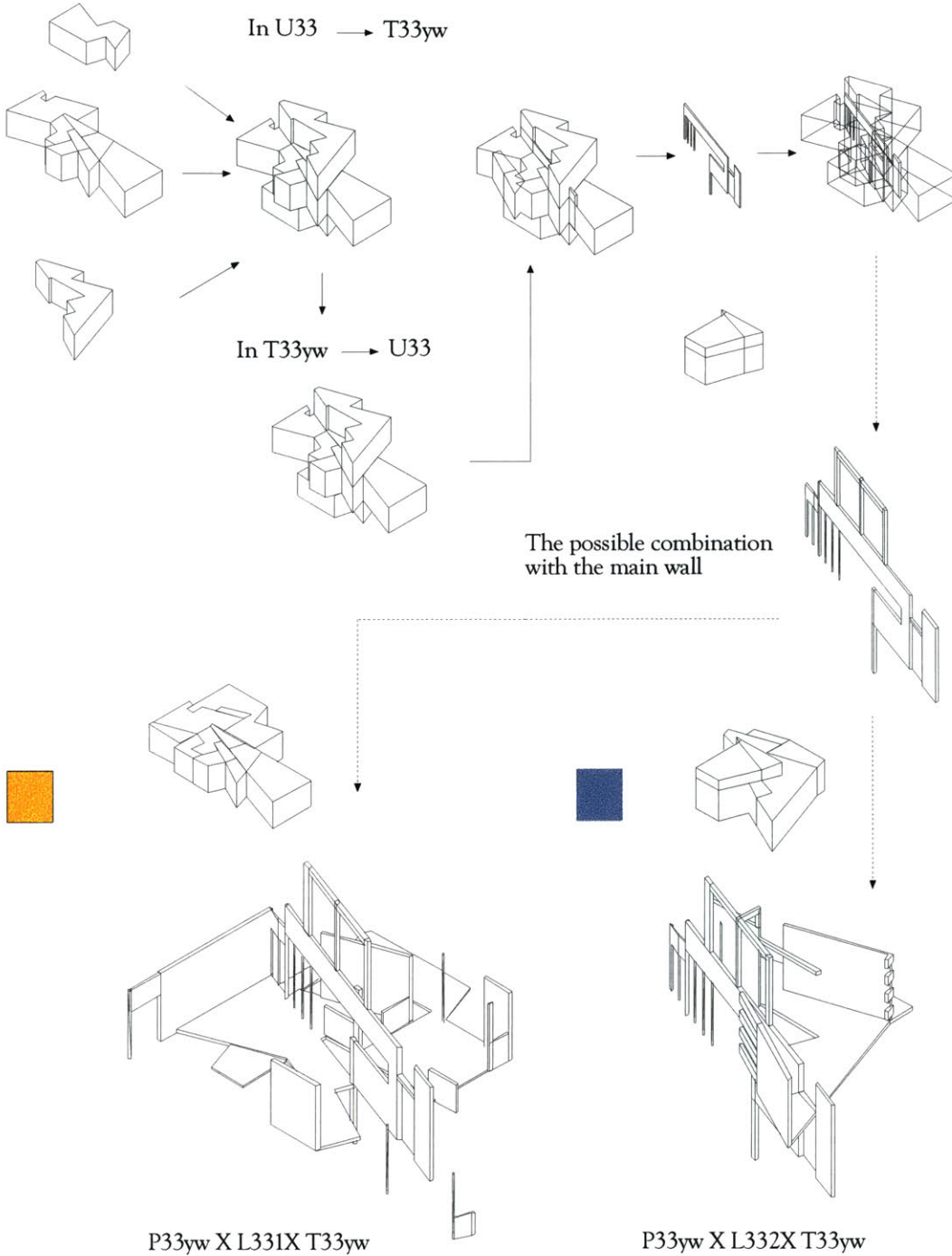
From the initial territories to the spatial components in P33w X L333

4.6.3.1 The Combination between Different Algebras

The different algebras can be combined using several meaning categories
 For example, when there are defined categories of the structural knowledge, the spatial components can be developed as follow :

In P33yw X L33yw

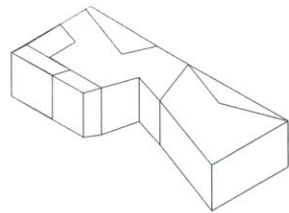
In P33yw X L33yw



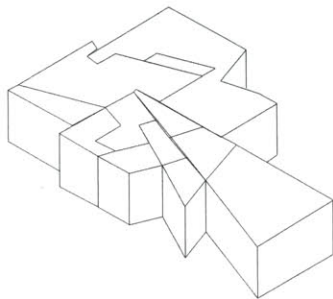
4.6.4 P33w X L33w



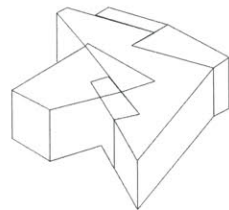
The design development is not restricted in any layers.
In U33, the architect can make a combination of the defined algebras.
Based on the new combination of the algebras, the architect can define the spatial blocks and recursively develop the components of the defined spatial blocks.



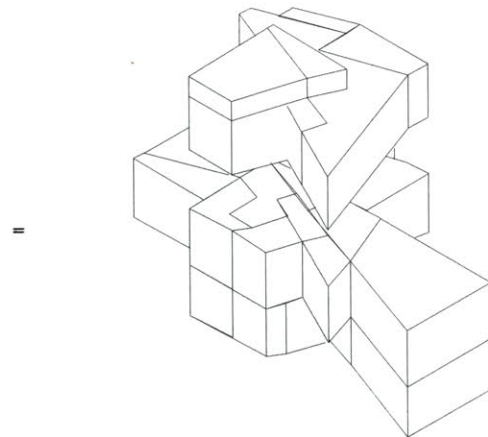
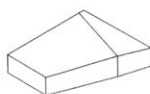
X



X

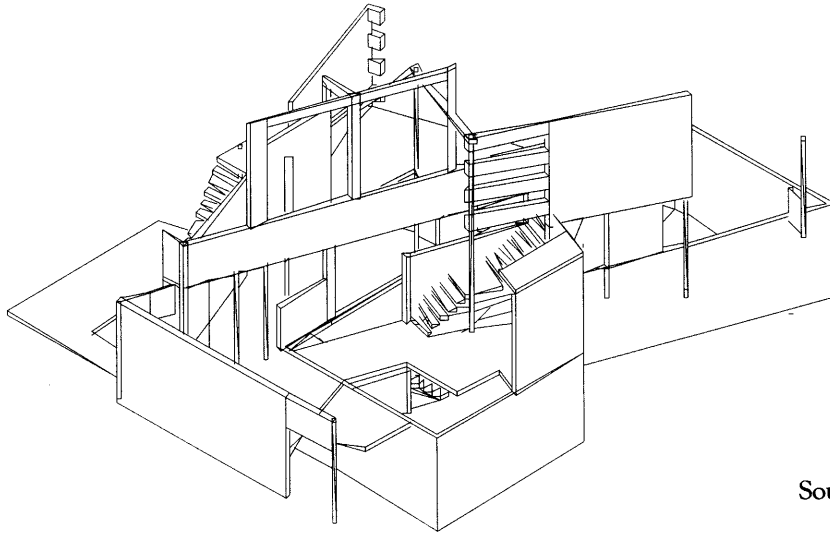


X

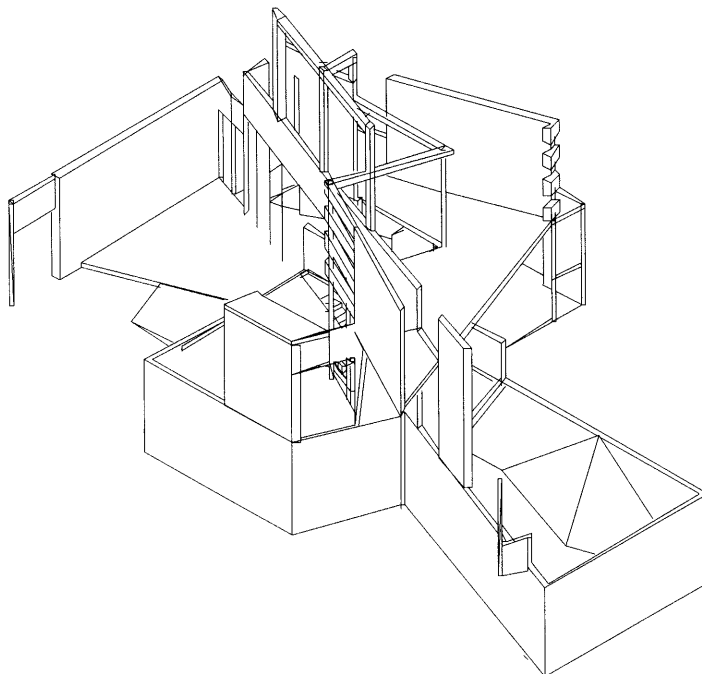


4.7 The Results of "Making-Folly" in various Combinations

The results of the combination : P33w X L33w X T33w



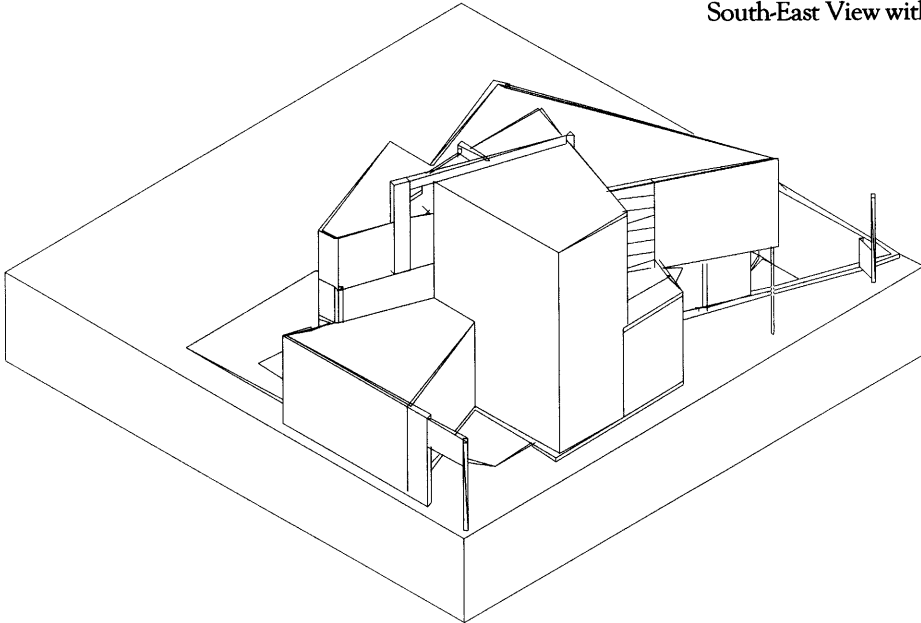
South-East View



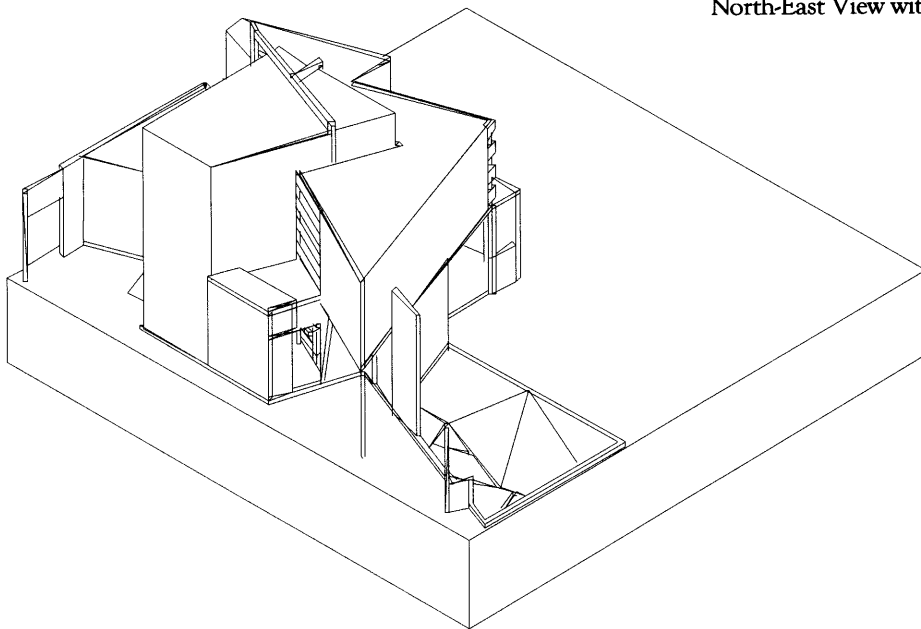
North-East View

The results of the combination : P33w X L33w X T33w X E33w

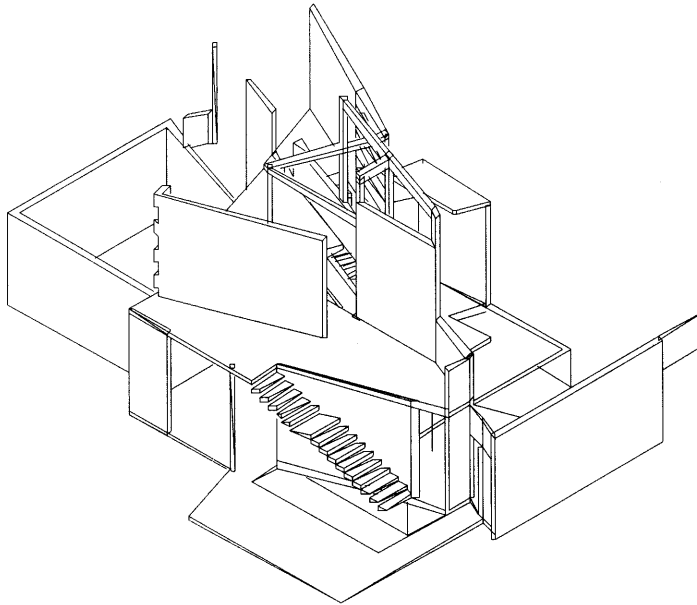
South-East View with the envelops



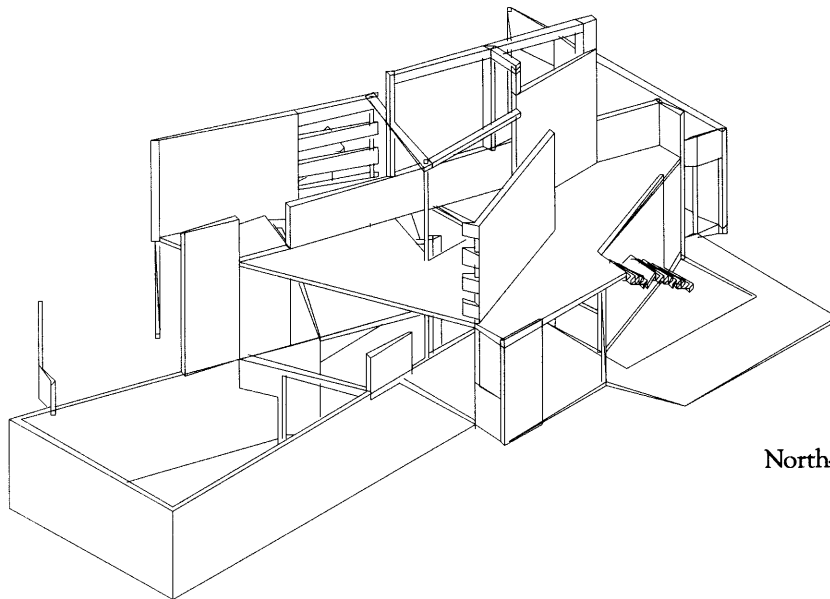
North-East View with the envelops



The results of the combination : P33w X L33w X T33w

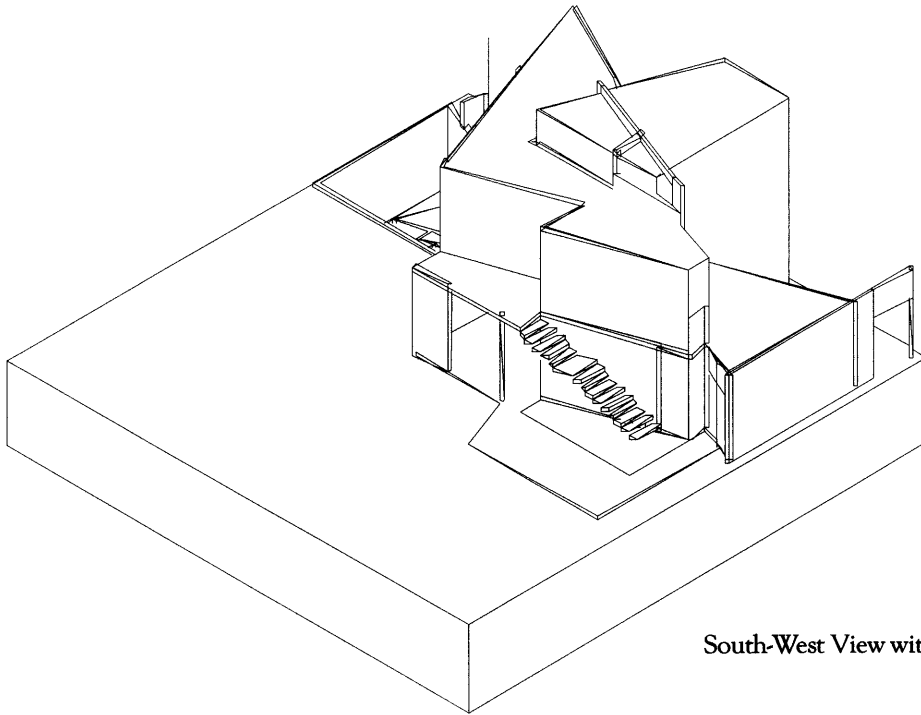


South-West View

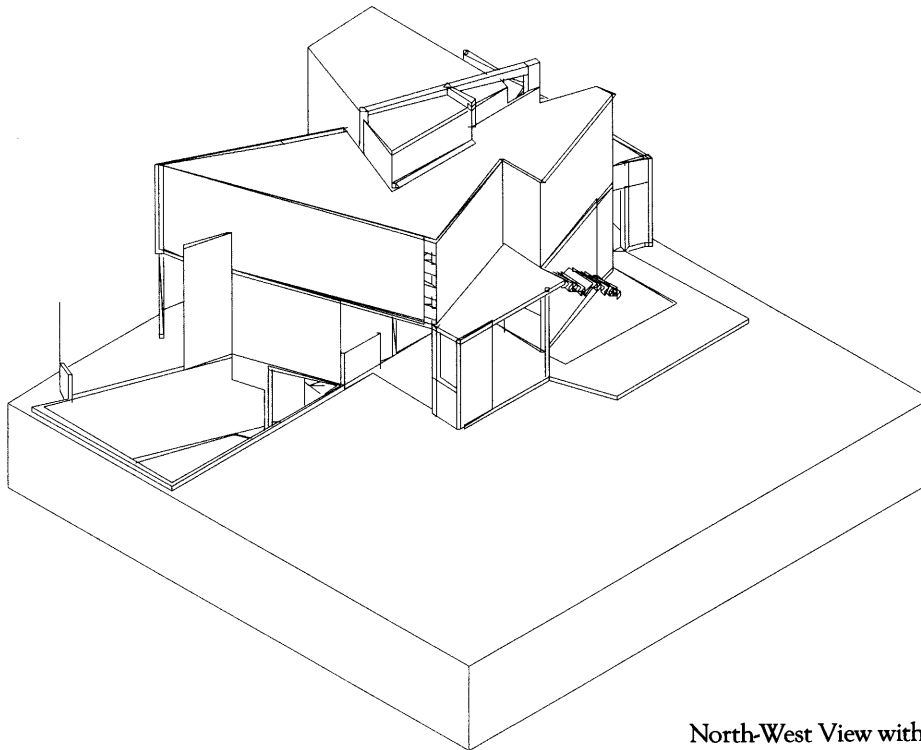


North-West View

The results of the combination : P33w X L33w X T33w X E33w

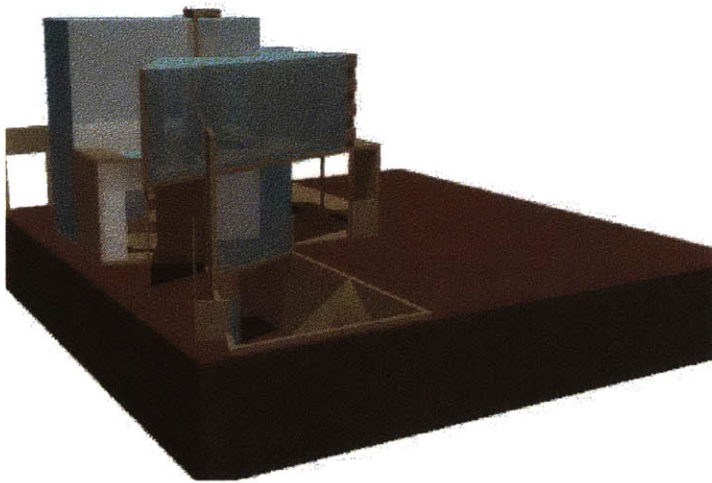
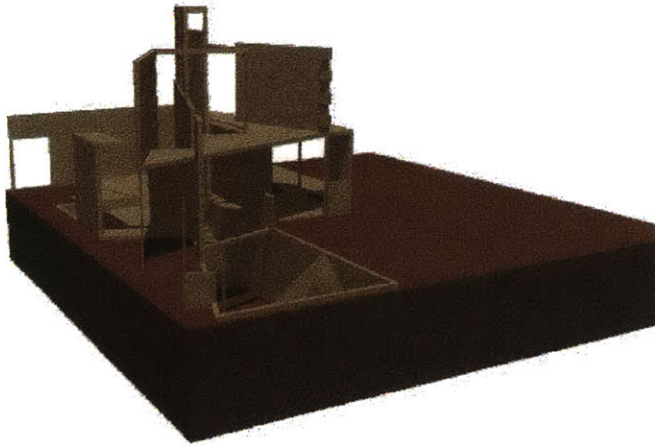


South-West View with the envelopes

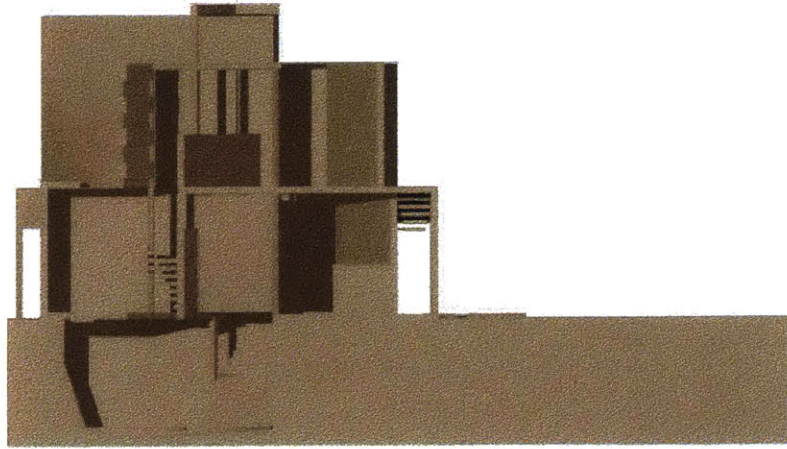


North-West View with the envelopes

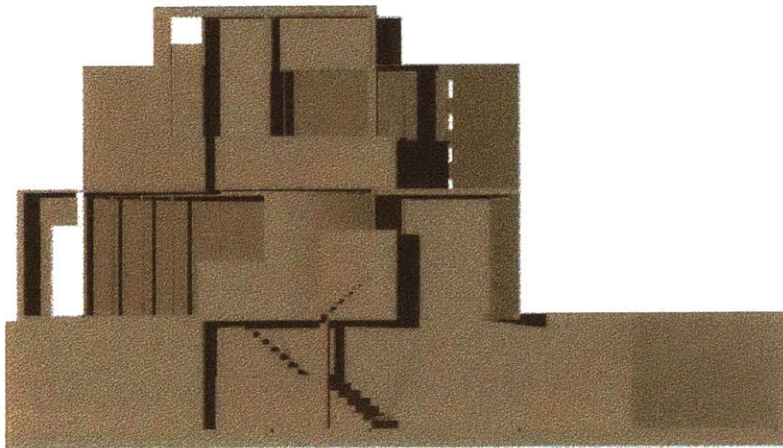
The Result of P33yw X L33yw X T33yw X M33 yw and Variation I



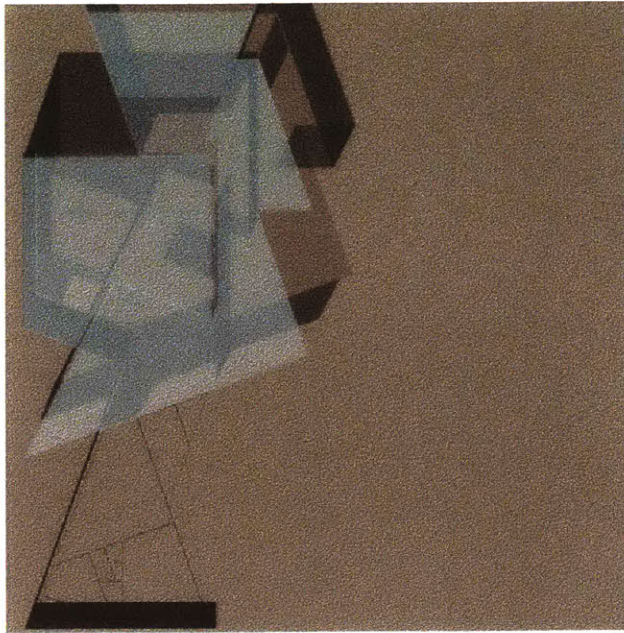
Section from North



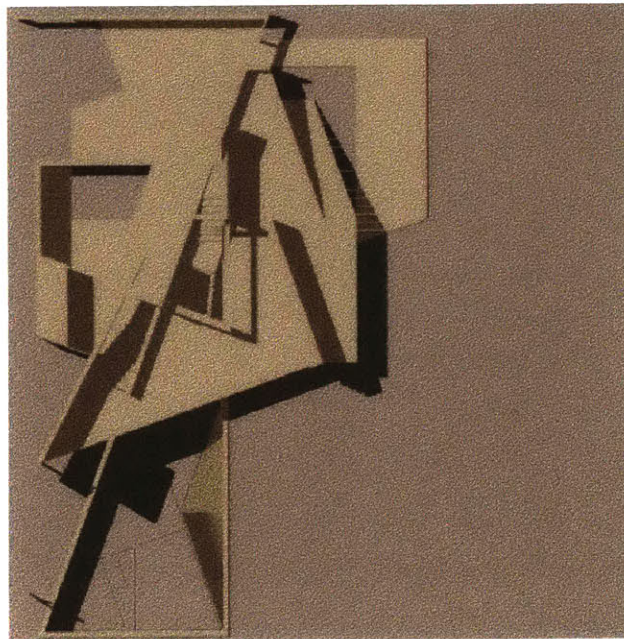
Section from East



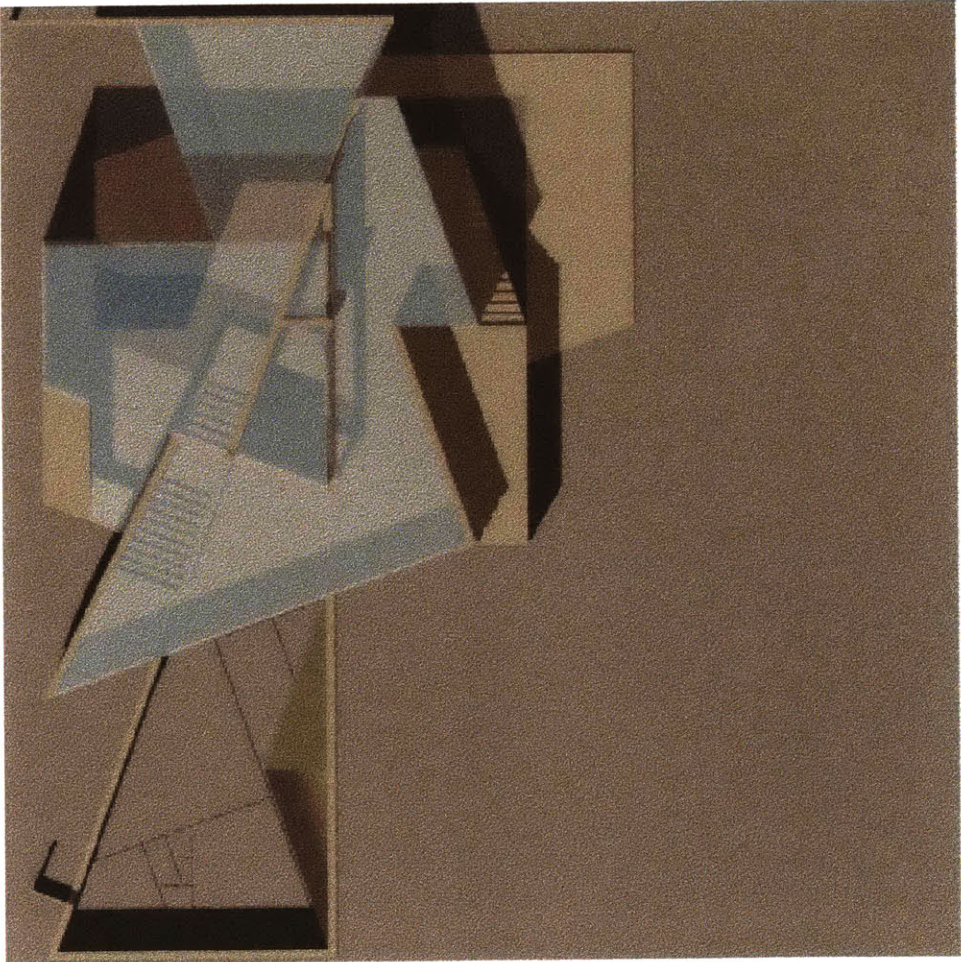
Envelopes from Top View



Structures from Top View



Site Plan



Chapter 5 Conclusion : C'

5.1 Symbols and Tools

Most architects have described their worlds with drawings and models. To make their worlds, they have used tools -such as pencils, paper, pieces of basswood, and various kinds of rulers- and symbols that are architectural forms. After the usage of a CAD system increased in the architectural design process, two different symbol systems have been created : formal symbol system, between an architect and the user-interface, and the mathematical symbol system, between the user-interface and the operating system inside the machine. Architects have found the difficulties in employing these tools in their design process because the conventional application of these tools to architectural design did not provide any solution to the problem of user-interface caused by the difference between these symbol systems. In this thesis, shape as mathematical means, and the different algebra, were introduced, not only as symbols, but also as tools applied to create the architect's own world combining these different symbol systems. In other words, sets of shapes, and the combination of different algebra, in Shape Grammar are suggested, not only as symbols to help an architect develop his/her design idea, but also as tools to make drawings in the design process using the CAD system.

5.2 Results

This thesis provides a model for applying Shape Grammar to create designs with formalization, data abstraction, and communication. Through the experimentation with "Making-Folly," the

formalization and data abstraction in the architectural design process are explained and tested. By formalizing several meanings into the specific categories, the architect manipulates the combination of different meaning categories to describe his/her design. By data abstraction, the architect organizes the records of the procedural decision as sets of shapes with different algebra which represents the formalized meaning category. In addition, the results of the experimentation show that an architect's design knowledge should be described by sets of shapes and the combination of different algebra. Finally, the shape itself is independent from the several meanings, and exists as a mathematical means with the combination of different algebra. Then, Architecture is bestowed on an architect as symbols and tools when *Architecture* is composed of sets of shapes and the different algebra.

By "Making-Folly" with formalization and data abstraction, the notions of spatial grids and initial territory allow for the transition of the environment of the shapes from U12 and U23 to become the boundary of the shape in U33. In formalizing the pictorial point of the shapes, the architect intentionally brings the deleted information into the drawing and develops the design by supplementing the deleted information between U12 and U33. Through this process, the architect stimulates his/her perception based upon the boundary relation of shapes. Then, the architect makes a data abstraction of the drawing that is sets of shapes. In the conventional design process, this method has been used for Parti investigation in Site analysis.

The space unit development provides the primary spatial organization of an architect's design like the spatial programming in the conventional design. Through this process, the architect formalizes the shapes in U33. From this process, the architect starts to formalize his/her design knowledge

into the specific meaning categories. After this, an architect should manipulate sets of shapes with a combination of the different categories. Based upon the space unit and the initial territory, the spatial block is introduced in order to develop design within a three-dimensional environment. The method of data abstraction in making the spatial block is the same as in making the initial territories because the algorithm of Shape Grammar is continuously applied throughout the process of data abstraction. In making the spatial block, an architect creates the deleted information as the initial territory and the spatial unit with different categories of meaning including U12, U23, and U33. Then, the architect uses his/her perception, based upon the pictorial transition among the spatial block, the spatial unit, and the initial territory, to make new shapes. Spatial components are proposed to form each part of the spatial blocks. With the combination of different meaning categories, the architect organizes this components into a whole. Also, after the architect formalizes the design process itself in the different categories, he/she applies the algorithm of Shape Grammar to create new shapes and algebra, or to change the old shapes with new one as the result of the combination of different algebras.

5.3 Advantages

With formalization and data-abstraction, the architect can interfere with the schemas from a current sequence of data-abstracted information for the new design. Since all data-abstracted information has its own shape, the individual components of the information can be easily edited by the architect by changing the order of the described design knowledge, or by replacing it based upon different design knowledge items in the specific categories. Finally, after the integration of this information is achieved based upon the formalization and data abstraction, the architect can

communicate to different people with sets of shapes and their description in different data layers of the computational tools.

5.4 The problems in making the practical software

First, in database access, existing user-interfaces only allow discrete entrance to one individual representation of knowledge-base without any related references/description that can be formulated during the design process. Second, in the exchange of data, we need to determine how technically to convert different data formats. The usage of a converter should also be considered ; it can synthesize different representations of design knowledge on the proper user-interface because different data formats are often used for different data layers. Third, as of now, there is no interpreter that accepts sets of shapes directly without changing them into programming texts/languages. Thus, to realize the real application of Shape Grammar to the design process, the development of such an interpreter is eagerly needed in order for an architect to use shapes, what we see, as tools.

5.5 Reflections

In this thesis, making the architectural design is described as an architect's world-making with sets of shapes and the different algebra as symbols and tools. A model of the architectural world-making process is proposed in "Making-Folly." There will be thousands of world-making ways, depending on the varying design knowledge of the architects in the design process. Thus, there is no clear definition of design knowledge itself because it's impossible to measure the extent of an

individual's design knowledge and life experience. However, if logic is accepted as the universal tool for describing, the architect can use his/her logic to define an individual's design knowledge by creating his/her own method because the method itself is the offspring of the logic. Thus, the only way to help an architect describe his/her world is to provide a logical method of describing it as one of world-making ways in the architectural design process.

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