INTRODUCTION TO SHAPE GRAMMARS

SIGGRAPH 2008

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INTRODUCTION TO SHAPE GRAMMARS

Lecturers: Mine Ozkar and Sotirios Kotsopoulos
Workshop instructors: Mine Ozkar and Sotirios Kotsopoulos

The theory of shape grammars defines a formalism to address the ambiguity that quantitative and symbolic computations mostly help us rule out in creative processes. The theory was first launched by Stiny and Gips in 1972 and has evolved into a groundbreaking pragmatist philosophy of shape and design since.

The course, composed of a 2 hour lecture and an optional one-day workshop for 10-12 participants, introduces the fundamentals of the theory and optionally a venue for attendees to put these to practice in a hands-on workshop. The lecture will focus on giving some basic knowledge of shapes, shape algebras, and shape rules in order to explain how shape grammars translate visual and spatial thinking into design computation. Multiple examples of generative designs produced using shape grammars will be presented. The workshop consists of one exercise where participants will explore spatial relations between a number of shapes, leading to the production of a series of designs to be built by hand, out of a prescribed material such as wooden blocks or paper.

Prerequisites

No prerequisites other than enthusiasm for shapes and keen interest in looking and seeing.

SYLLABUS

INTRODUCTION TO SHAPE GRAMMARS

Lecturers: Mine Ozkar and Sotirios Kotsopoulos
Class time: 1 hr 45 mins.

Topics:

Part I – The theory

1. What are shape grammars?
2. Describing shape grammars in terms of *seeing* and *counting*
3. Describing shape grammars as a rule-based system
4. Decompositions
5. The mathematical set-up of shape grammars
6. Basic elements: shapes, labels, weights
7. Shape algebras
8. Shape boundaries
9. Part relations: embedding, overlapping, discrete elements
10. Euclidean transformations
11. Maximal shapes
12. Boolean operations on shapes

Part II – Applications in design and design education 13. Recapitulation of the main computational devices

13. Recapitulation of the main computational devices of shape grammars
14. Shape grammar applications in design analysis
15. Shape grammar applications in design synthesis

Introduction to Shape Grammars

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Sotirios Kotsopoulos, Ph.D., MIT

Slide 1

Outline

Part I – The theory

1. What are shape grammars?
2. Describing shape grammars in terms of *seeing* and *counting*
3. Describing shape grammars as a rule-based system
4. Decompositions
5. The mathematical set-up of shape grammars
6. Basic elements: shapes, labels, weights
7. Shape algebras
8. Shape boundaries
9. Part relations: embedding, overlapping, discrete elements
10. Euclidean transformations
11. Maximal shapes
12. Boolean operations on shapes

Part II – Applications in design and design education

13. Recapitulation of the main computational devices of shape grammars
14. Shape grammar applications in design analysis
15. Shape grammar applications in design synthesis

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Outline of the class showing the topics addressed.

Part I

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Title page to Part I

What are shape grammars?

a) A computation theory

that defines a formalism to represent visual (and spatial) thinking;

that handles **ambiguities** which symbols do away with.

b) A philosophy of looking at the world

that is not through learnt or imposed definitions but through those that have a **practical meaning** at a given point in time;

that values the continuity of matter and flexibility in how to cut it up into its parts.

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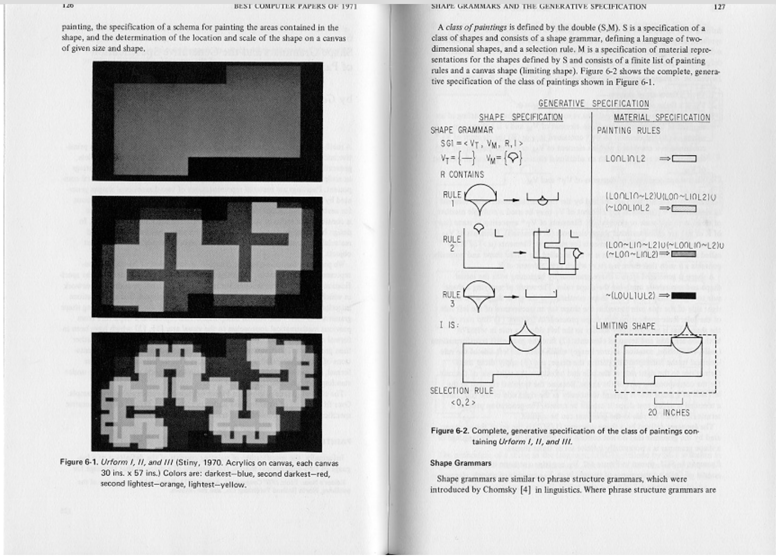
Shape grammars may be described at two levels. Firstly, it is a computation theory that defines a formalism to represent visual, or even spatial, thinking. At the same time, it handles ambiguities which conventional digital computing does away with. The phrase shape grammar more literally refers to visual design grammars. At the second level, the theory represents a philosophy of looking at the world that is not through learnt or imposed decompositions (definitions) but through those that have a practical meaning at that point in time.

What are shape grammars?



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painting, the specification of a schema for painting the areas contained in the shape, and the determination of the location and scale of the shape on a canvas of given size and shape.

Figure 6-1. *Urform I, II, and III* (Stiny, 1970. Acrylics on canvas, each canvas 30 ins. x 57 ins.) Colors are: darkest—blue, second darkest—red, second lightest—orange, lightest—yellow.

SHAPE GRAMMARS AND THE GENERATIVE SPECIFICATION 127

A *class of paintings* is defined by the double (S,M). S is a specification of a class of shapes and consists of a shape grammar, defining a language of two-dimensional shapes, and a selection rule. M is a specification of material representations for the shapes defined by S and consists of a finite list of painting rules and a canvas shape (limiting shape). Figure 6-2 shows the complete, generative specification of the class of paintings shown in Figure 6-1.

Figure 6-2. Complete, generative specification of the class of paintings containing *Urform I, II, and III.*

Shape Grammars

Shape grammars are similar to phrase structure grammars, which were introduced by Chomsky [4] in linguistics. Where phrase structure grammars are

Stiny and Gips, Shape Grammars and Generative Specification, in Best Computer Papers of 1971

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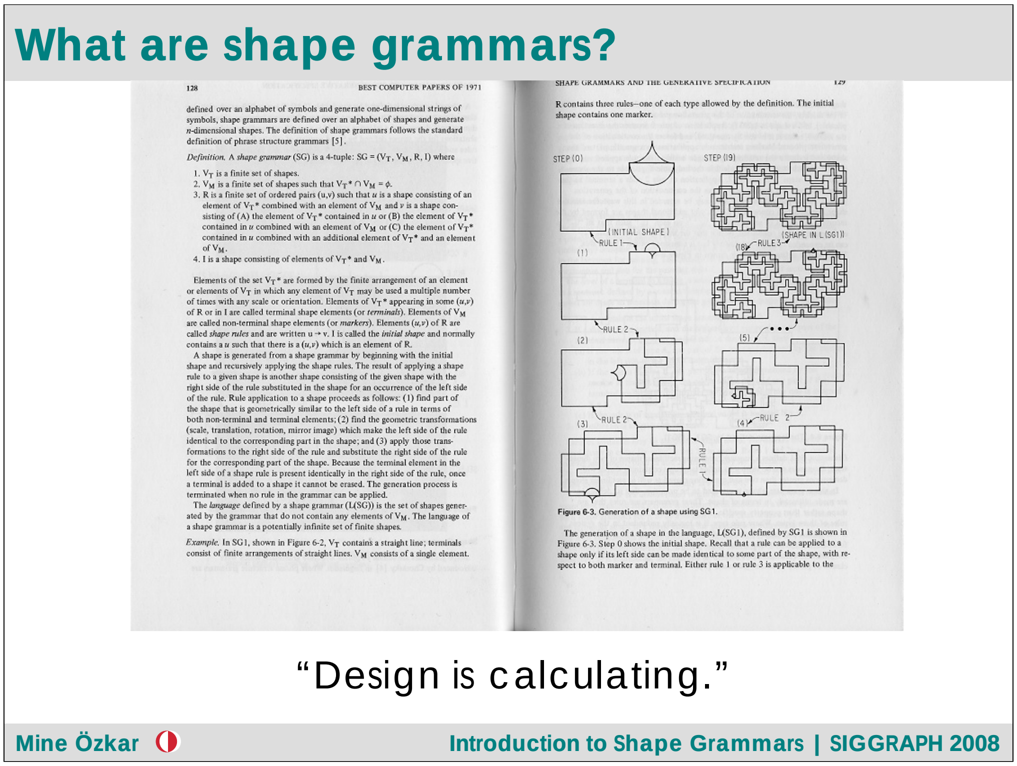
Shape grammars were first introduced in the beginning of the 70s by George Stiny and James Gips. Published as one of the best computer papers of 1971, their “Shape Grammars and Generative Specification” paper introduced a set of generative rules for a few paintings done by Stiny himself.

The three paintings in the article, are from a series called Urform. These are going to be the basis for illustrating various concepts of shape grammars in this class.



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defined over an alphabet of symbols and generate one-dimensional strings of symbols, shape grammars are defined over an alphabet of shapes and generate *n*-dimensional shapes. The definition of shape grammars follows the standard definition of phrase structure grammars [5].

Definition. A *shape grammar* (SG) is a 4-tuple: SG = (V_T, V_M, R, I) where

1. V_T is a finite set of shapes.
2. V_M is a finite set of shapes such that $V_T^* \cap V_M = \phi$.
3. R is a finite set of ordered pairs (u,v) such that *u* is a shape consisting of an element of V_T^* combined with an element of V_M and *v* is a shape consisting of (A) the element of V_T^* contained in *u* or (B) the element of V_T^* contained in *u* combined with an element of V_M or (C) the element of V_T^* contained in *u* combined with an additional element of V_T^* and an element of V_M.
4. I is a shape consisting of elements of V_T^* and V_M.

Elements of the set V_T^* are formed by the finite arrangement of an element or elements of V_T in which any element of V_T may be used a multiple number of times with any scale or orientation. Elements of V_T^* appearing in some (*u*,*v*) of R or in I are called terminal shape elements (or *terminals*). Elements of V_M are called non-terminal shape elements (or *markers*). Elements (*u*,*v*) of R are called *shape rules* and are written u → v. I is called the *initial shape* and normally contains a *u* such that there is a (*u*,*v*) which is an element of R.

A shape is generated from a shape grammar by beginning with the initial shape and recursively applying the shape rules. The result of applying a shape rule to a given shape is another shape consisting of the given shape with the right side of the rule substituted in the shape for an occurrence of the left side of the rule. Rule application to a shape proceeds as follows: (1) find part of the shape that is geometrically similar to the left side of a rule in terms of both non-terminal and terminal elements; (2) find the geometric transformations (scale, translation, rotation, mirror image) which make the left side of the rule identical to the corresponding part in the shape; and (3) apply those transformations to the right side of the rule and substitute the right side of the rule for the corresponding part of the shape. Because the terminal element in the left side of a shape rule is present identically in the right side of the rule, once a terminal is added to a shape it cannot be erased. The generation process is terminated when no rule in the grammar can be applied.

The *language* defined by a shape grammar (L(SG)) is the set of shapes generated by the grammar that do not contain any elements of V_M. The language of a shape grammar is a potentially infinite set of finite shapes.

Example. In SG1, shown in Figure 6-2, V_T contains a straight line; terminals consist of finite arrangements of straight lines. V_M consists of a single element.

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R contains three rules—one of each type allowed by the definition. The initial shape contains one marker.

Figure 6-3. Generation of a shape using SG1.

The generation of a shape in the language, L(SG1), defined by SG1 is shown in Figure 6-3. Step 0 shows the initial shape. Recall that a rule can be applied to a shape only if its left side can be made identical to some part of the shape, with respect to both marker and terminal. Either rule 1 or rule 3 is applicable to the

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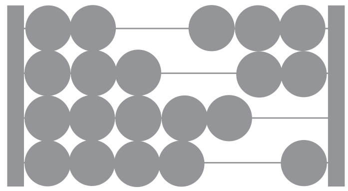
Stiny (2006) claims that design is calculating while expanding the meaning of calculation to visual thinking via his theory of shape grammars. The motto “design is calculating,” was a starting point in 1971 as well. The reasoning behind a visual product was described using a grammar-like formalism with a vocabulary, a set of rules, and a series of computations that produced designs as if they were “sentences”.

Seeing and Counting



Computing --- *computare* (to count)

Calculating --- *calculus* (pebble)

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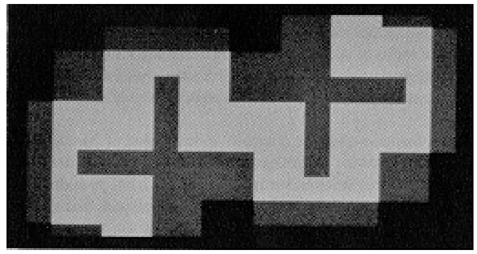
Stiny often equates the terms design, visual reasoning and calculation. This claim firstly enunciates an understanding that design has reasoning within. Secondly, in the theory of shape grammars, the terms calculation and computation, which are often interchangeably used, are seen under a new light. Counting is at the root of computing and calculating. Visual calculation on the other hand, gives room for seeing as well as for counting.

Seeing and Counting



How does one calculate with shapes?

Urform II, George Stiny, 1970, acrylic on canvas 30 ins x 57 ins, blue, red, orange, yellow.

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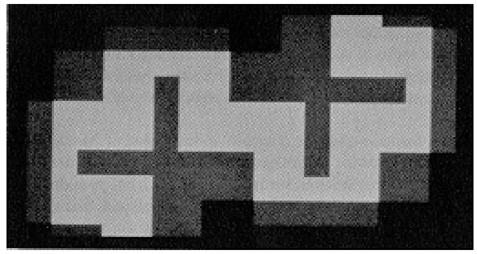
How does one calculate with shapes? Do visual kinds of thinking exclude calculation? Or does calculation reduced to counting exclude visual and spatial kinds of thinking? Stiny argues that one has to really 'see' in order to count and that 'seeing' is where creativity lies.

Seeing and Counting



Counting requires discrete parts.

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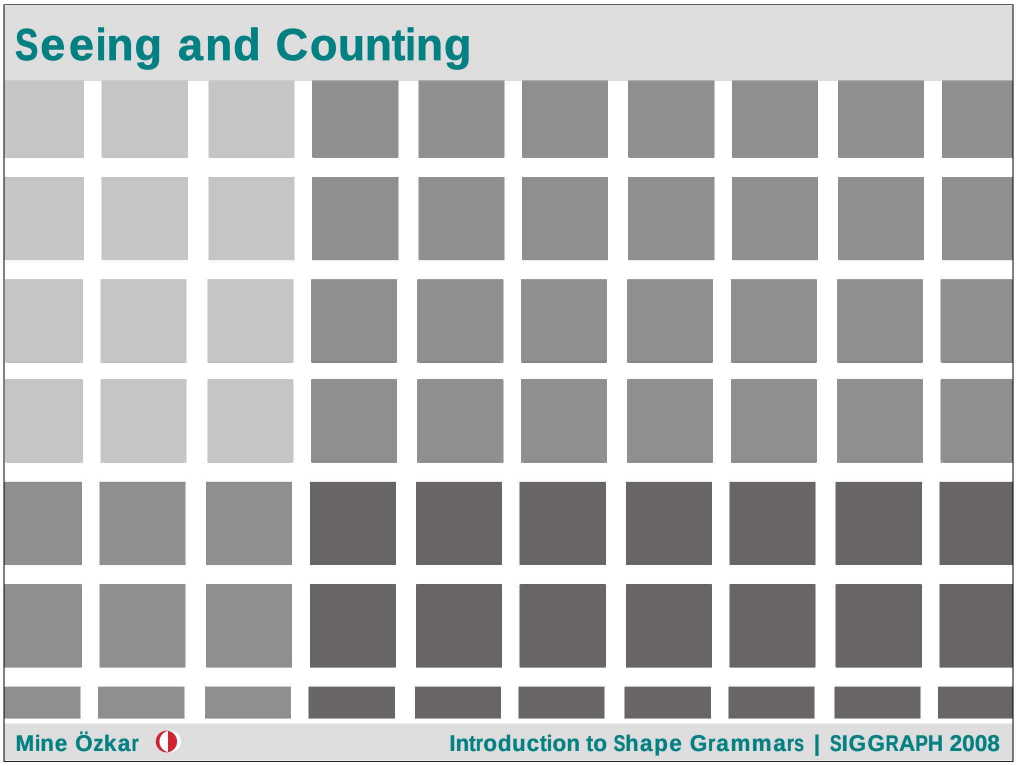
As in the abacus, counting requires discrete parts.



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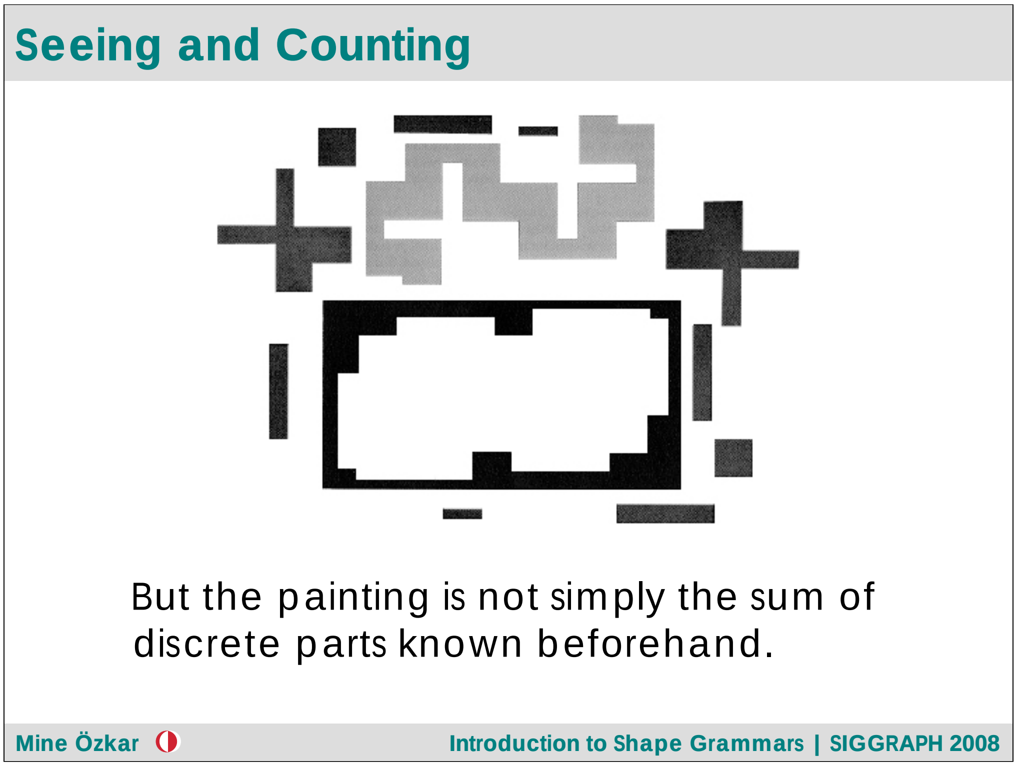
One can divide Urform II into smallest possible discrete bits, perhaps into dots on the screen, each assigned with a different color code. These smallest primitives are countable but irrelevant in the perception of the whole. This image shows a small section of the imagined screen of dots.



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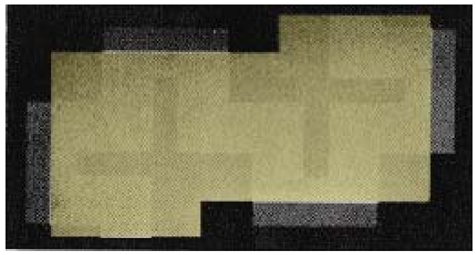
Alternatively, one can divide Urform II into some obvious parts, distinct therefore countable. However, the painting is possibly a much more dynamically formed formal arrangement and is not simply a sum of discrete parts that were known before hand.

Seeing and Counting



One can see different parts to count.

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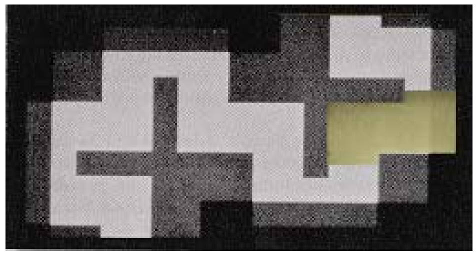
There are always some other parts to see. Moreover, these may be the meaningful parts, or parts that are surprisingly merged with one another. In the visual world, there are wholes that coexist, and they share parts, or parts of parts. This image shows a part that is not readily there but can be seen.

Seeing and Counting



Once seen, parts can be counted.

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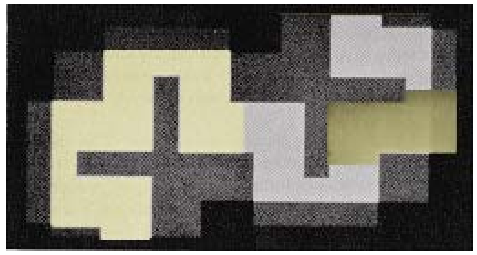
Calculation then, is to see first, then count. This way, we can calculate with different parts each time we look at Urform II. The shape shown exists in ten instances in Urform II: one large, nine small ones.

Seeing and Counting



Varying parts and wholes coexist.

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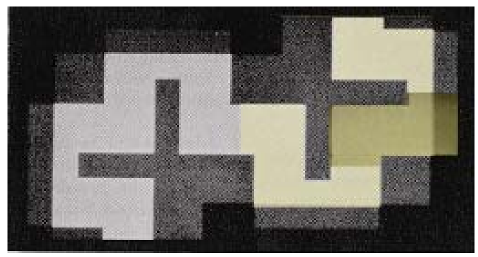
Seeing and Counting



Parts and wholes coincide.

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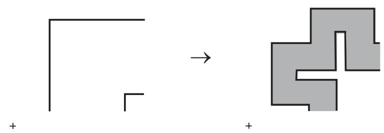
Seeing and Counting



The shape grammar way of seeing and counting is visual rules that tell: “see the left side and then replace it with what is on the right.”

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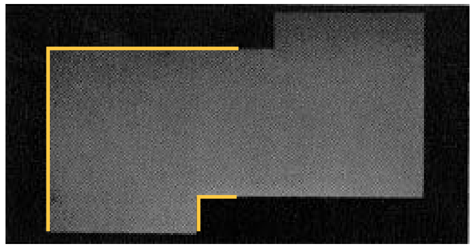
Stiny and Gip’s explanation for the process behind the Urform series is a visual rule that tells one to see the left side to replace it with the right side. The illustration shows one such possible rule. These kinds of rules form the basis of shape grammars.

Seeing and Counting



I can see two instances of the shape on the left side of the rule.

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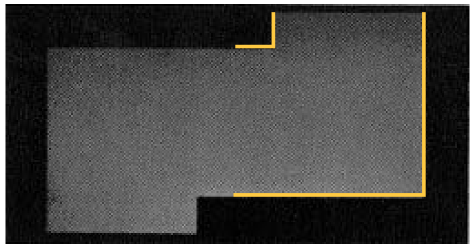
This is how it basically works. Looking for the left side in an initial shape set, in this case Urform I, one can see two instances of it.

Seeing and Counting



I apply my rule to one of them.

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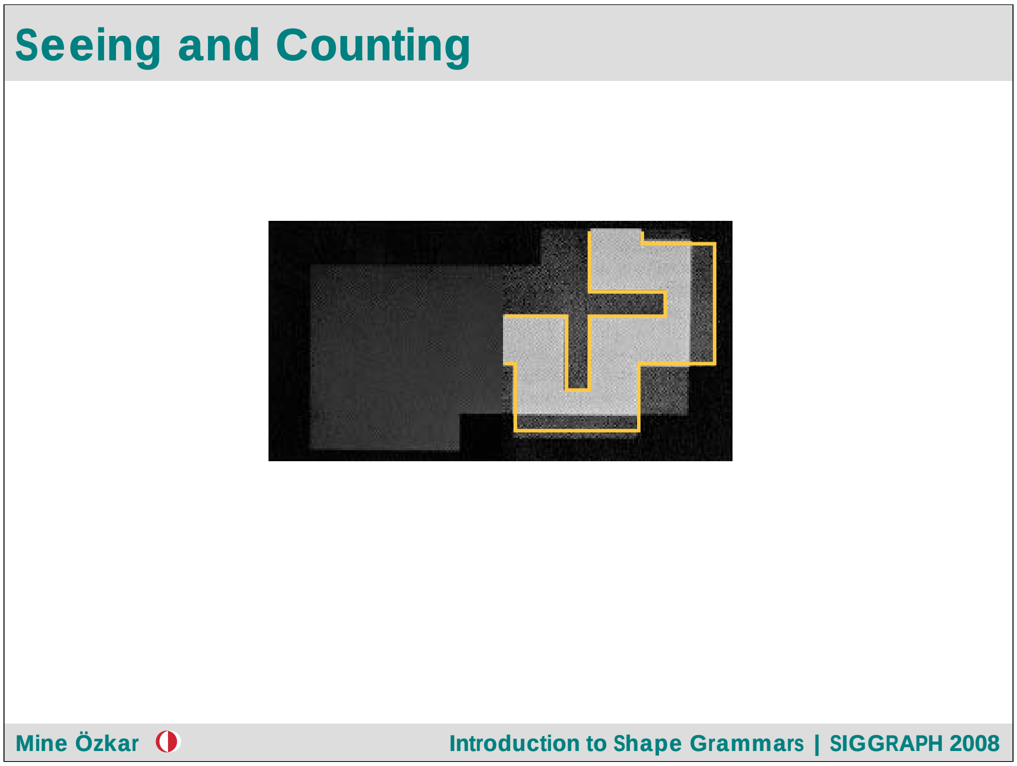
The second one is rotated 180°.



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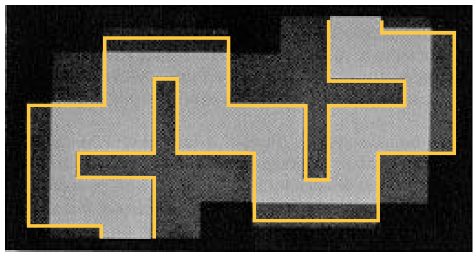
The rule is applied to the second one shown.

Seeing and Counting



Or to both.

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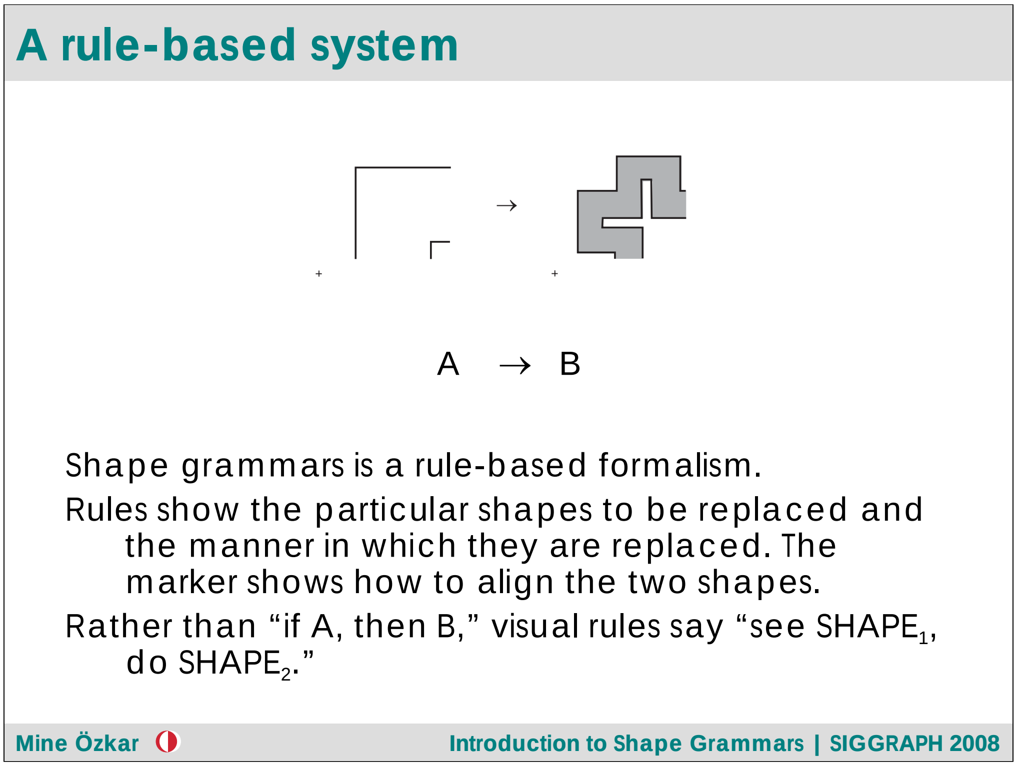
The rule is then applied to the first instance.



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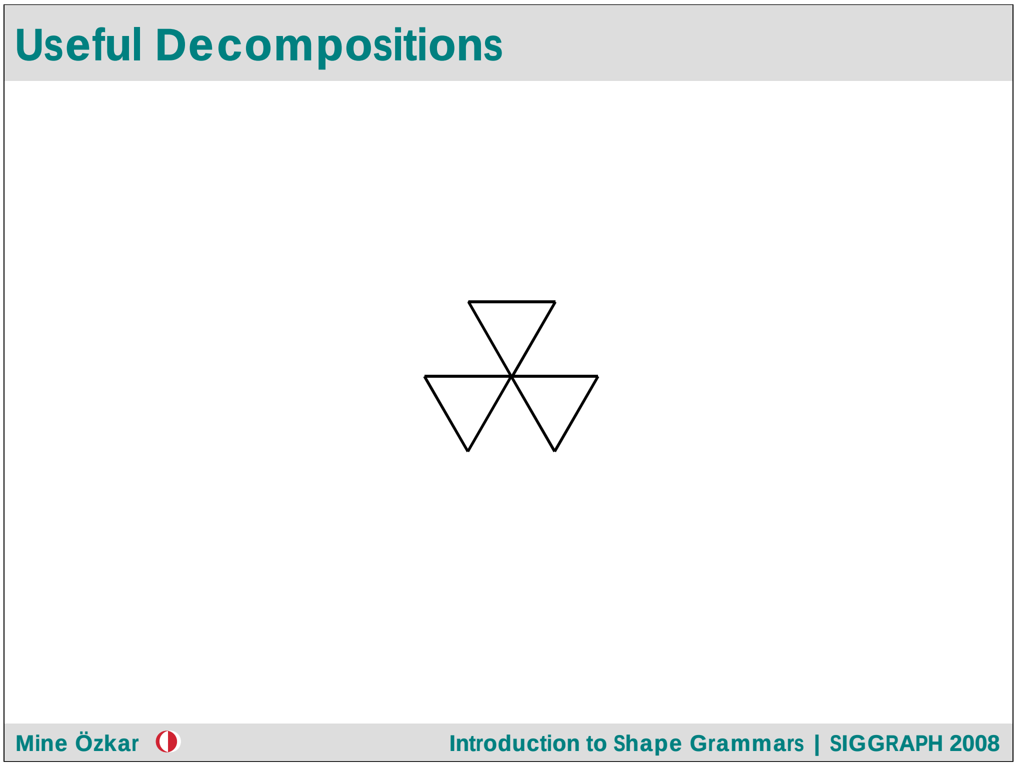
A shape rule has two steps when applied: a recognition of a particular shape shown on the left side and its possible replacement shown on the right side.

The defined rule is operational. The arrow indicates an action.

The unique feature of a shape rule is that the left and right side are visually considered. As opposed to symbols, shapes can be looked at and seen differently.



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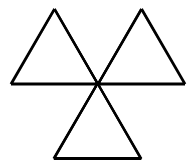
Because shapes are visual, they can be decomposed in infinitely many ways. There should be no preconceived decompositions and primitives acquired through such operations. Visual rules, which are subjective, will call for various decompositions.

For example, let us look at one of the most popular examples Stiny (2006) gives to explain why we need to be computing with visual rules. There is a shape, composed of three triangles that will be rotated around its center. The only catch is, it will be rotated by a rule that says “rotate triangle.”

Useful Decompositions



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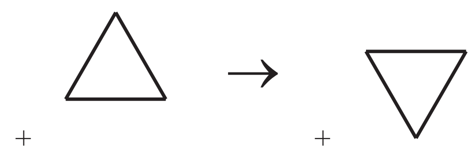
Useful Decompositions



The visual rule: rotate an equilateral triangle 180^{o} around its center.

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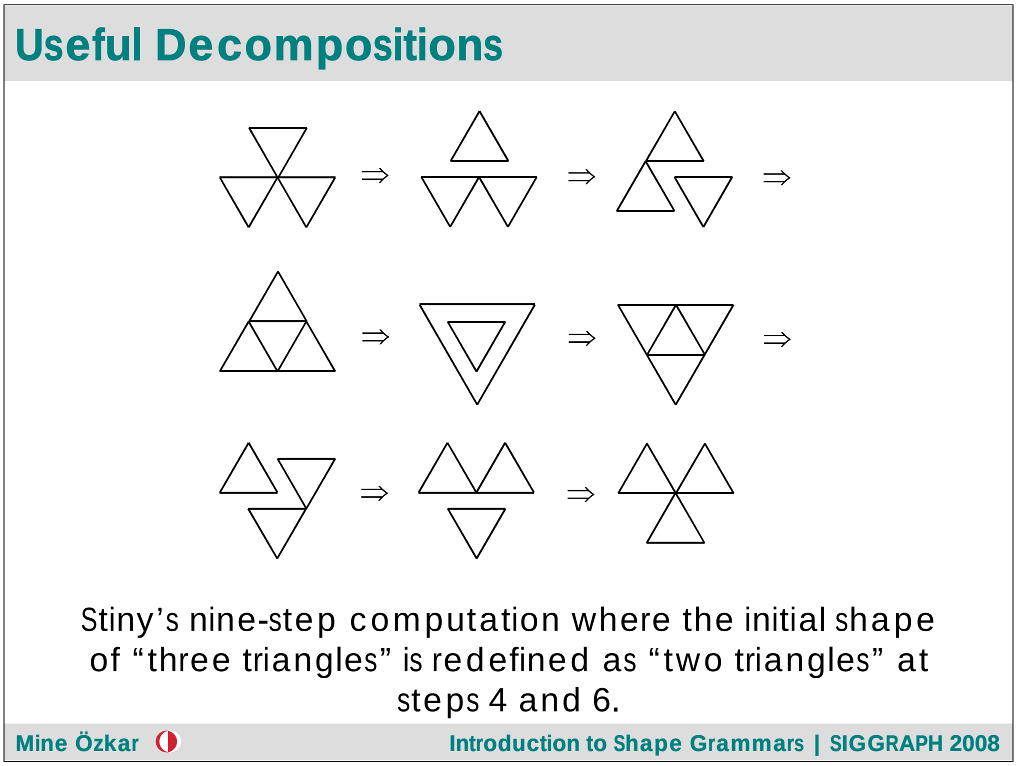

Slide 25

In the nine step computation, Stiny shows that the initial definition of the shape, that is 'three triangles', changes in step 4 and then back again in step 6. Decompositions should not be timeless. The initial shape could have been drawn as three triangles, six lines, or 9 lines. Whatever the history, a new definition can always come up while working with shapes. Ambiguity should be maintained.

The mathematical set-up

Shapes, Labels and Weights
Shape algebras
Boundaries of shapes
Part relations of shapes
Euclidean transformations
Maximal shapes
Boolean operations with shapes

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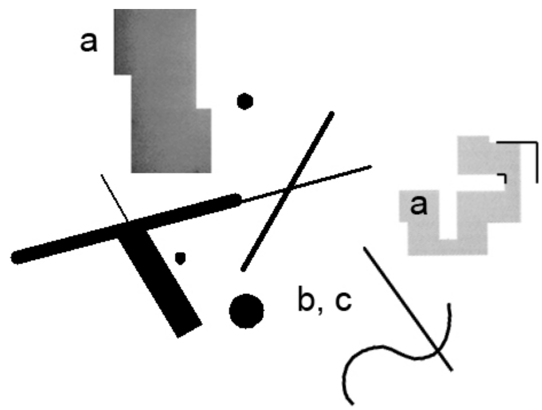
The mathematical set-up of the theory includes general definitions of shapes, shape, weight and label algebras, shape boundaries, part relations, Euclidean transformations, maximal shapes, and Boolean operations with shapes.

Shapes, labels, weights



Basic elements of shapes are points, lines, planes, and solids, with **labels,** if necessary, to give abstract information about them, and **weights,** as indicators of magnitudes of some formal attributes.

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Shapes can be points, lines, planes, solids or combinations of these. Shapes also can have labels that indicate additional information about them and weights that indicate the magnitude of some formal properties. Labels are useful for adding more constraints necessary for tasks such as establishing the order in which rules are applied in computations.

Shape algebras

$U_{0\,0}$	$U_{0\,1}$	$U_{0\,2}$	$U_{0\,3}$
	$U_{1\,1}$	$U_{1\,2}$	$U_{1\,3}$
		$U_{2\,2}$	$U_{2\,3}$
			$U_{3\,3}$

Shapes are categorized under different shape algebras. The left index shows the dimension of the basic elements, and the right index shows the dimension in which these basic elements are combined in shapes.

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Basic elements in shapes are categorized under different shape algebras. The indices indicate the dimension of the basic element and the dimension in which these elements are combined and transformed.

Shape algebras

$\mathbf{U_{0\,0}}$	$\mathbf{U_{0\,1}}$	$\mathbf{U_{0\,2}}$	$\mathbf{U_{0\,3}}$
	$U_{1\,1}$	$U_{1\,2}$	$U_{1\,3}$
		$U_{2\,2}$	$U_{2\,3}$
			$U_{3\,3}$

Atomic algebras
(of points in space)

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All shape algebras that have 0 for the first index are atomic. A basic element within these algebras can only be a point and has no parts other than itself. Symbols, for example, are elements of these algebras and have a dimension of zero. Also, units that add up to a sum of units belong in these algebras but in those that have the second index higher than 1.

Shape algebras

$\mathbf{U_{0\,0}}$	$U_{0\,1}$	$U_{0\,2}$	$U_{0\,3}$
	$U_{1\,1}$	$U_{1\,2}$	$U_{1\,3}$
		$U_{2\,2}$	$U_{2\,3}$
			$U_{3\,3}$

Boolean algebra
(of zeroes and ones)

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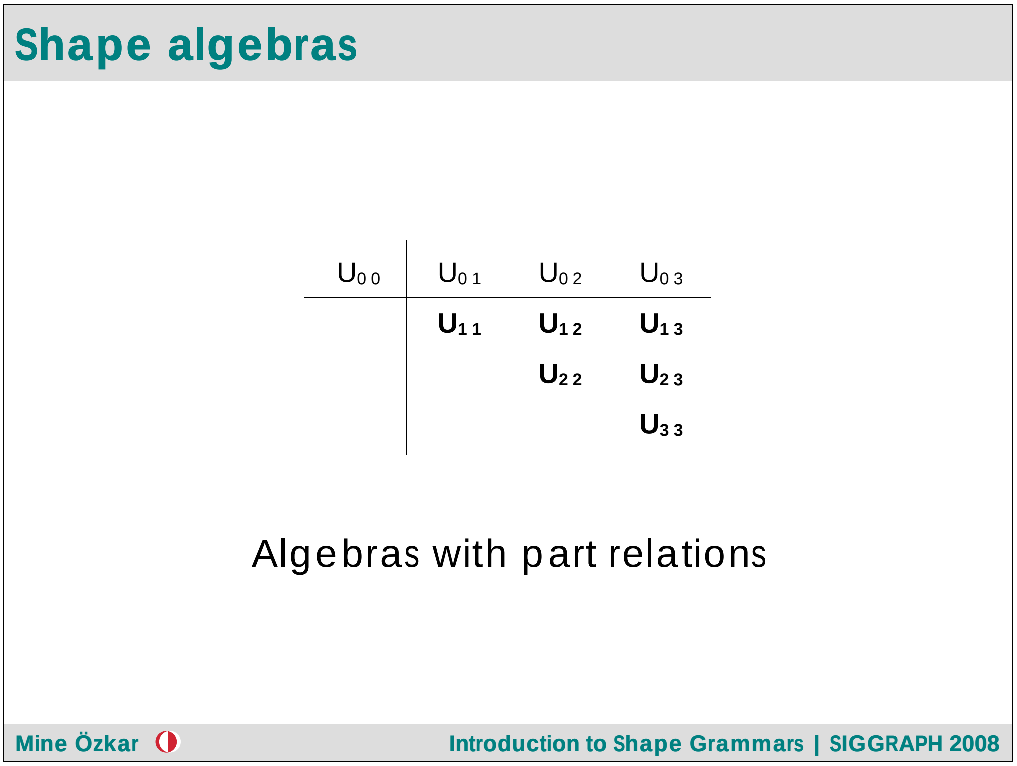
The algebra where both indices are 0 is Boolean. There are only two values, null and one. Something either is or is not.



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All algebras with the indices equal to or larger than one, show different properties than atomic algebras. They do not have atoms but shapes with parts such as lines, planes, solids, etc. The number of members within a set in one of those algebras does not have to be finite. For example, in algebra U_{11}, on a line space, there can be infinitely many lines of different lengths.

Shape boundaries

Algebra	Basic elements	Number of parts	Boundary shapes
$U_{0\,j}$	points	finite	none
$U_{1\,j}$	lines	infinite	$U_{0\,j}$
$U_{2\,j}$	planes	infinite	$U_{1\,j}$
$U_{3\,j}$	solids	infinite	$U_{2\,j}$

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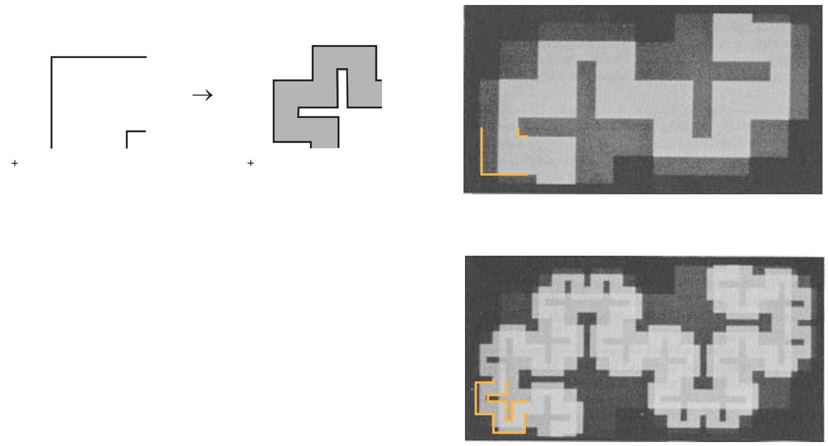
There is a clear relation between the categories of basic elements belonging to different algebras. The boundaries of solids are plane shapes, the boundaries of planes are line shapes, the boundaries of lines are points whereas points have no boundary.

Shape boundaries



U_{12} and U_{22} algebras are combined when utilizing the relation between shapes and shapes on their boundaries.

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Shape boundaries constitute a practical relation between shapes, which, in turn, helps us in the way we visually think.

The rule in the illustration is in U_{12}+U_{22} algebra and is used to create the design which is in U_{22} algebra. Parts of plane boundaries appear as line shapes that are utilized in generating the final form with planes.

Part relations

Three types of part relations are those of

overlapping,
embedded, or
discrete shapes

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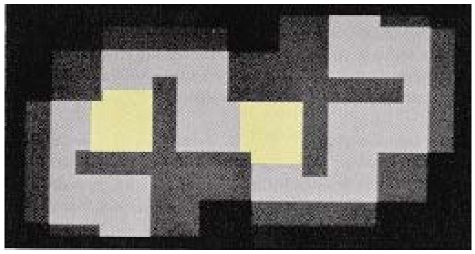
Part relations are what differentiates shapes from atoms. Three kinds of part relations are between overlapping, embedding and discrete shapes.

Part relations



discrete

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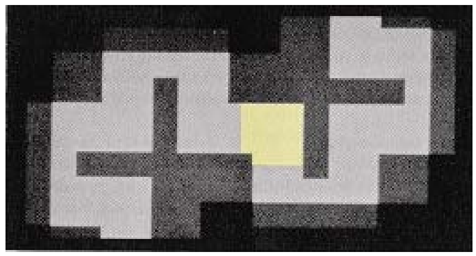
Planes with no shared boundaries are discrete.

Part relations



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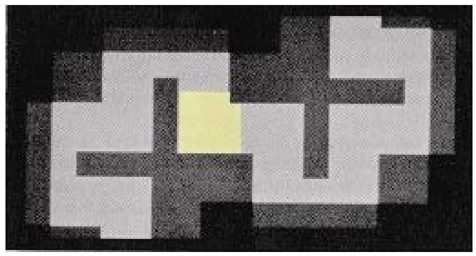
However shapes that share a common boundary but have no part in common are also discrete.

Part relations



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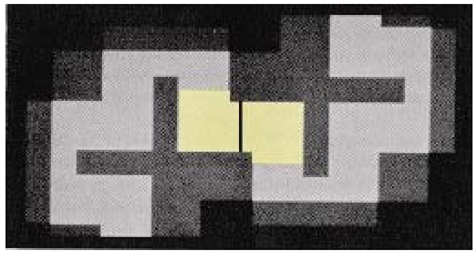
The two planes highlighted in slides 36 and 37 share a common boundary, but share no plane parts.

Part relations



discrete

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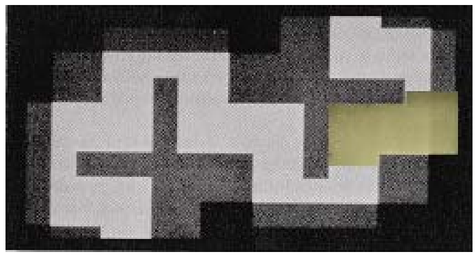
Thus they are discrete despite the common boundary.

Part relations



overlapping

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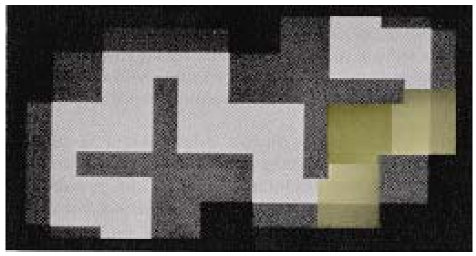
Slide 39

Those shapes that share a common part are said to overlap.

Part relations



overlapping

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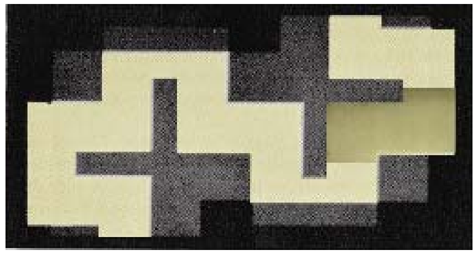
Slide 40

The two planes shown share a common part, and are overlapping. Both shapes have parts that are not common with the other.

Part relations



embedding

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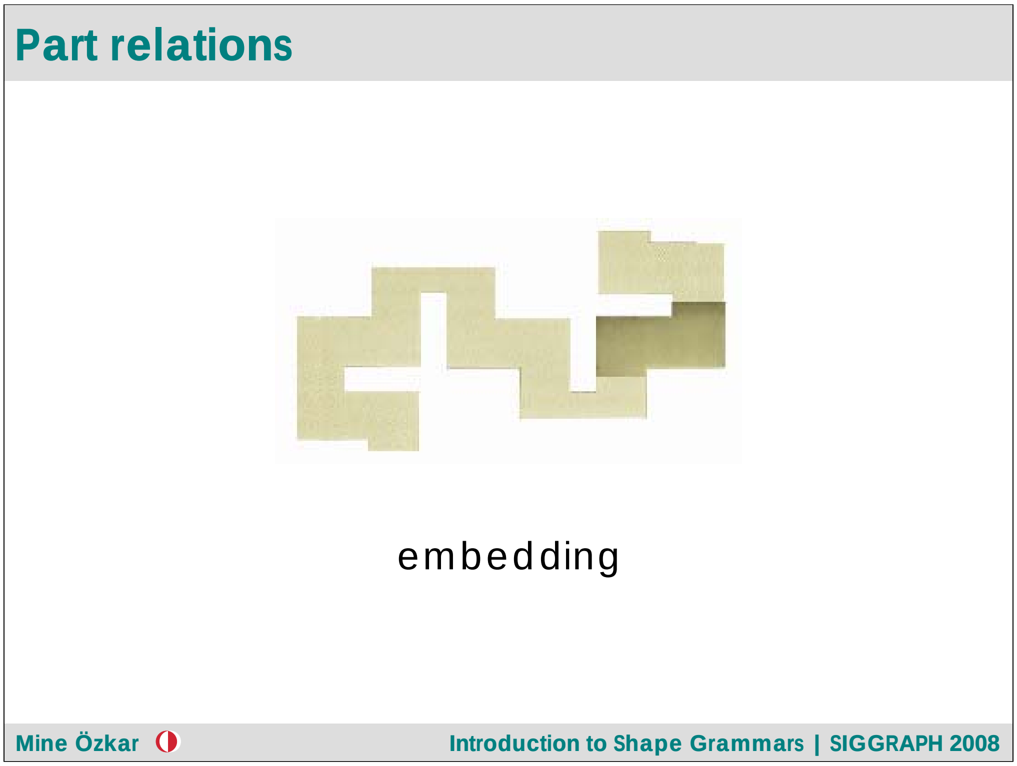
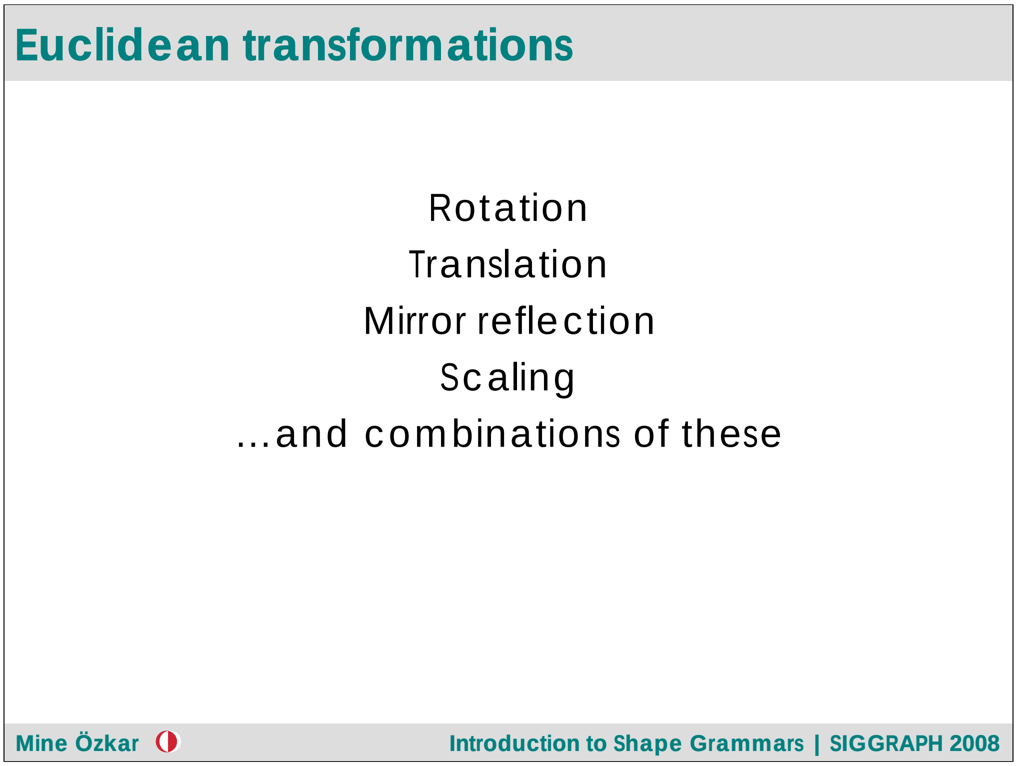
Slide 41

If two shapes have common parts and at least one of these shapes has no part that is not a part of the other, then this shape is said to be embedded within the other.



Slide 42

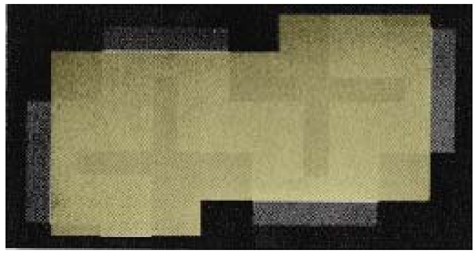
The darker shape is embedded within the larger and lighter colored shape.



Slide 43

Euclidean transformations that are used in shape grammars are translation, scaling, rotating and reflecting along with their combinations. In the example of the painting, I can relocate the left side of the rule in so many places using these transformations. I can scale it down and up, I can see its rotations, I can see its reflections, and I can see it in multiple places, which are illustrated in slides 44 through 48.

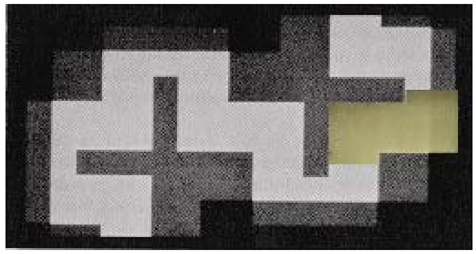
Euclidean transformations



Slide 44

Let us start with any perceived shape within Urform II.

Euclidean transformations



scaling

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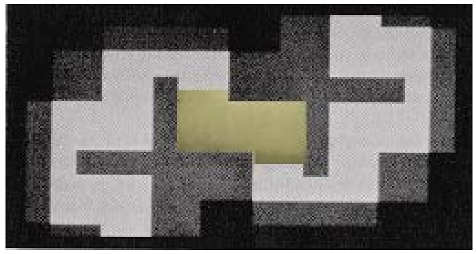
Slide 45

I can identify it in a smaller size.

Euclidean transformations

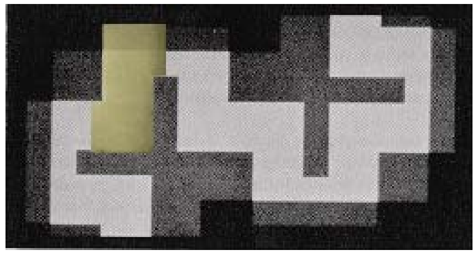


reflection

Slide 46

I can identify it in a mirror reflection.

Euclidean transformations



rotation

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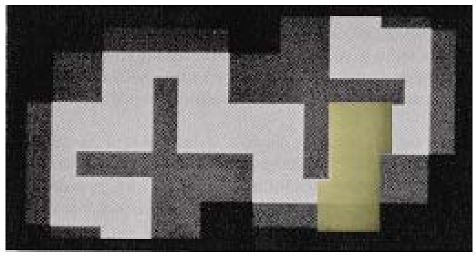
Slide 47

I can identify it in a 90º counter clock wise rotation.

Euclidean transformations



translation

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Slide 48

I can identify it in another location in the painting.

Boolean operations on shapes

Sum

$A + B$

Difference

$A - B$

Product

$A \cdot B = A - (A - B)$

Symmetric difference

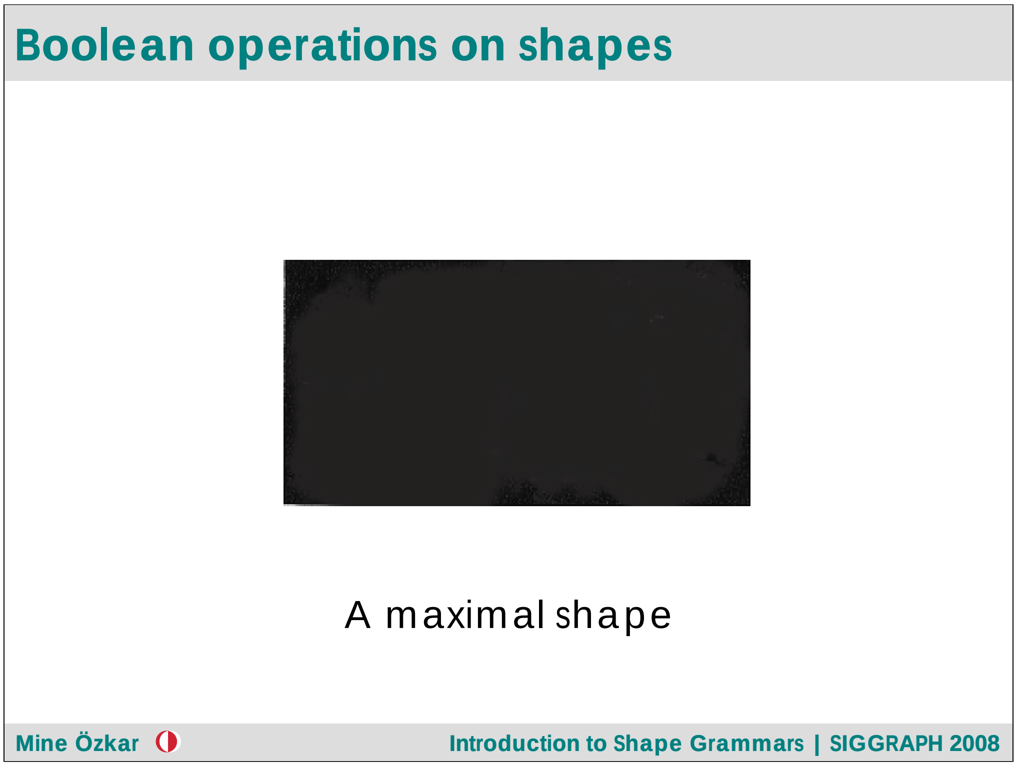
$A \oplus B = (A - B) + (B - A)$

$A \oplus B = (A + B) - (A \cdot B)$

Slide 49

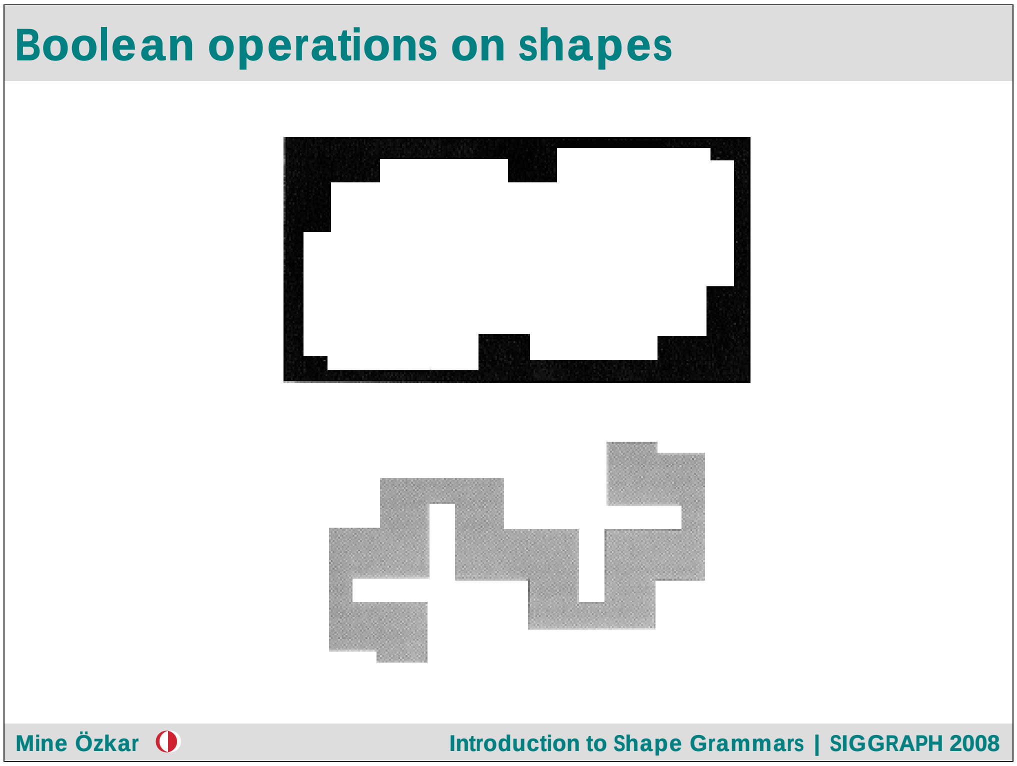
Within the defined shape algebras, we can add and subtract shapes of the same kind of basic elements. We can also take their unions and products.

We can combine algebras to do Boolean operations on different kinds of basic elements in parallel.



Slide 50

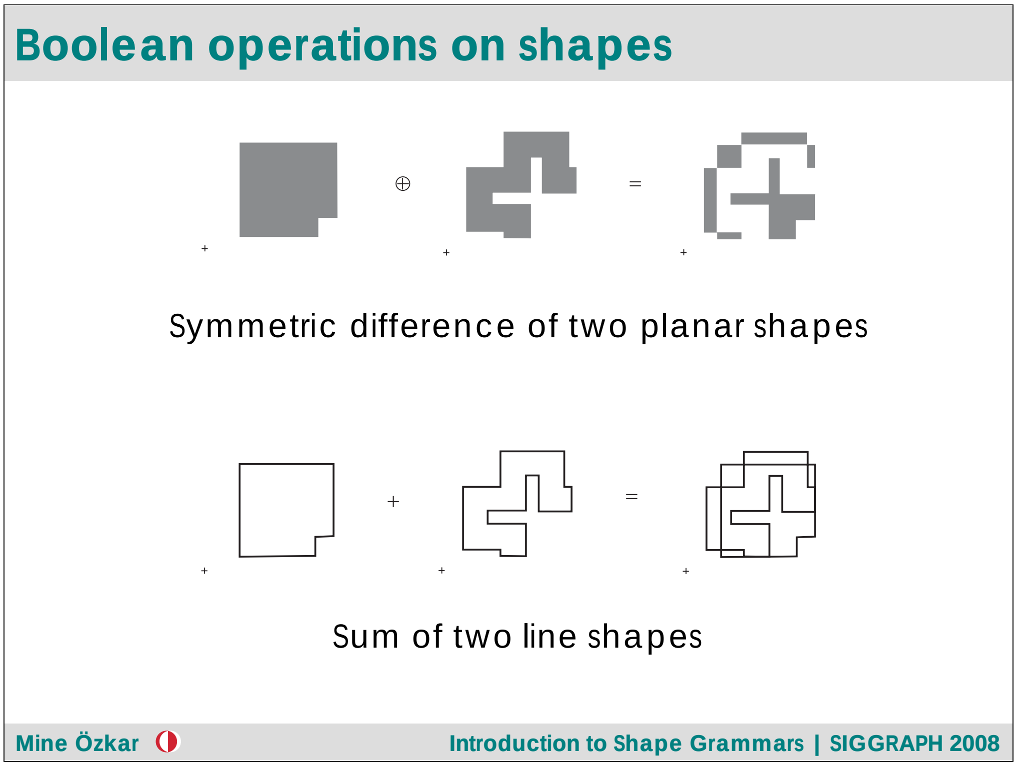
Operating outside the Weight algebra, the union of all planes is as shown and is called the maximal plane. A maximal shape can be defined as the union of all existing parts that are either overlapping with or embedded in one another. Planes that are in discrete relation through a shared boundary can also form a maximal shape in union.



Slide 51

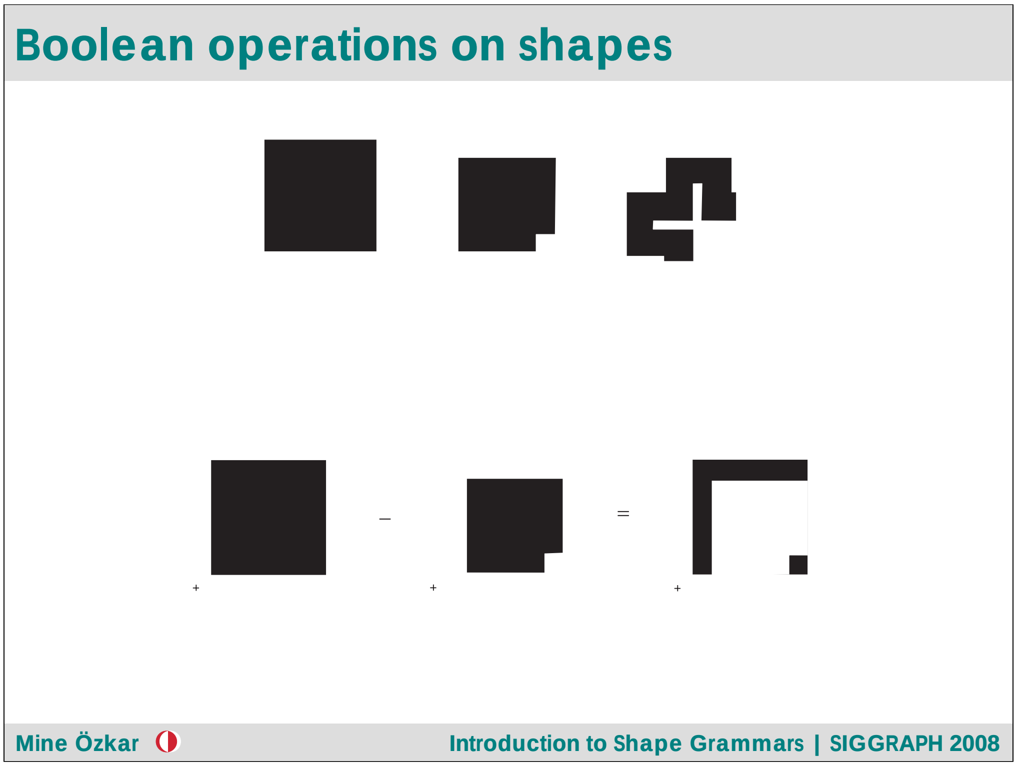
If considered within the defined Weight algebra, for each tone of grey, other maximal shapes appear. These are separately unions of shapes with overlapping and embedding relations and with discrete relations where they share at least a boundary.

The maximal shapes shown are also members of the set of discrete shapes shown at the beginning of the class as a possible decomposition.



Slide 52

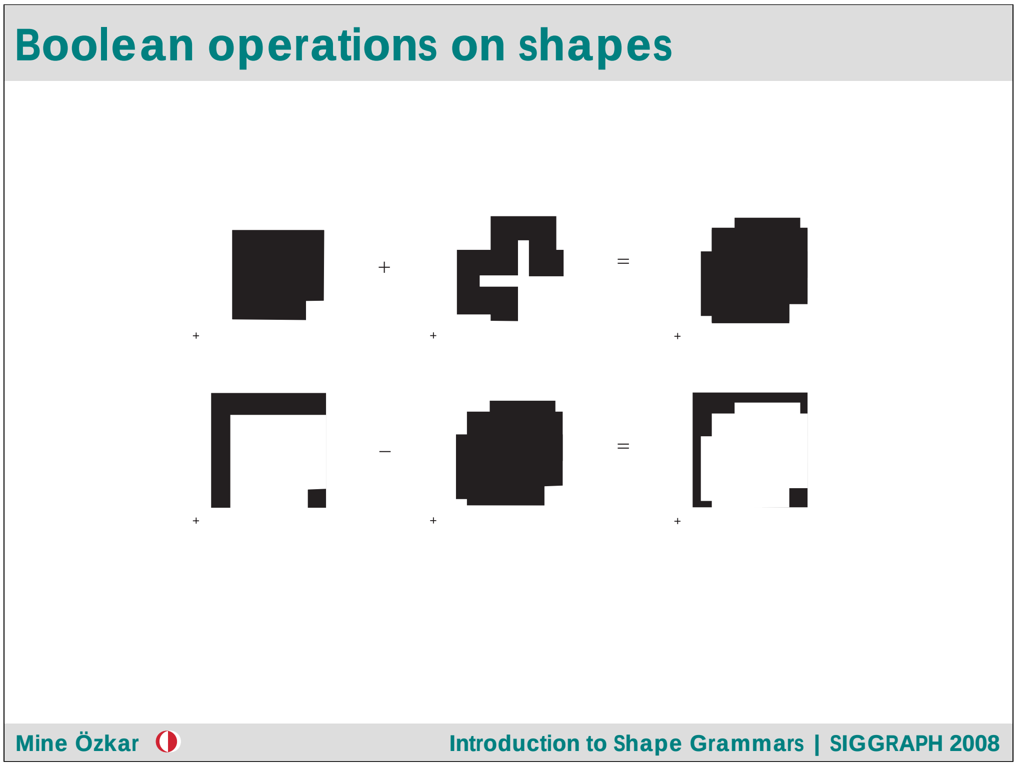
Here are illustrations to possible Boolean operations on shapes based on the Urform series. The first operation shows the symmetric difference of two plane shapes of the same weight in U_{22} whereas the second operation shows the sum of the boundaries of these two planes in U_{12}.



Slide 53

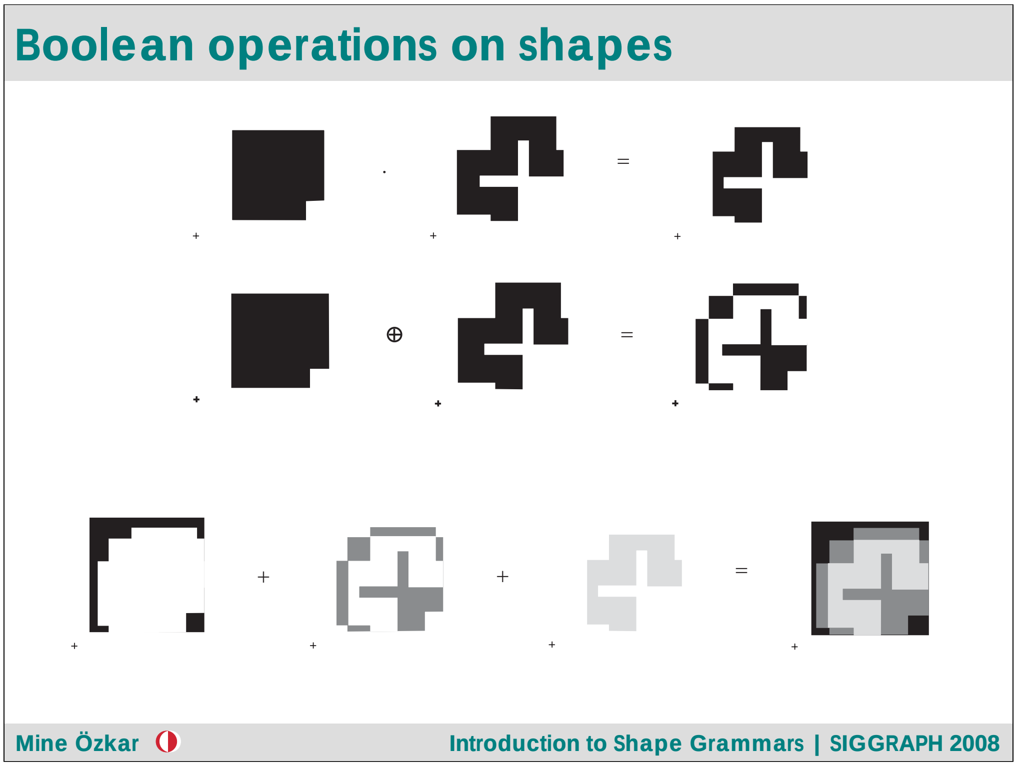
In another set of illustrations are a series of Boolean operations on shapes of equal weight value in U_{22}.

Let us assume that there are three initial shapes. Firstly, the difference of shapes one and two is calculated.



Slide 54

Then, the sum of shapes two and three is calculated and subtracted from the result of the first step.



Slide 55

Continuing with the operations, the product of shapes two and three is followed by the symmetric difference of the two. From this series of operations, three new shapes emerge. Finally, all of these three are assigned different weights and summed up.

Up until this point, we have shown how shape algebras, Boolean operations and part relations all work together for computing with shapes. In the next part, more examples, from actual applications, will be utilized to illustrate these concepts further.

Part II

Slide 0

Shape Grammar Applications

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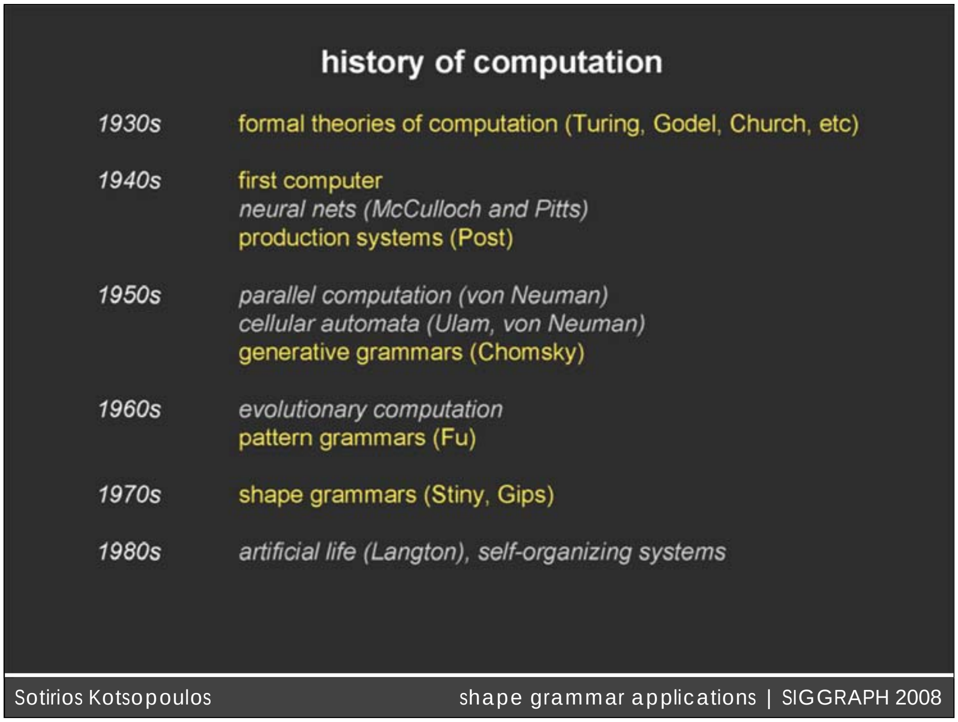
Slide 1

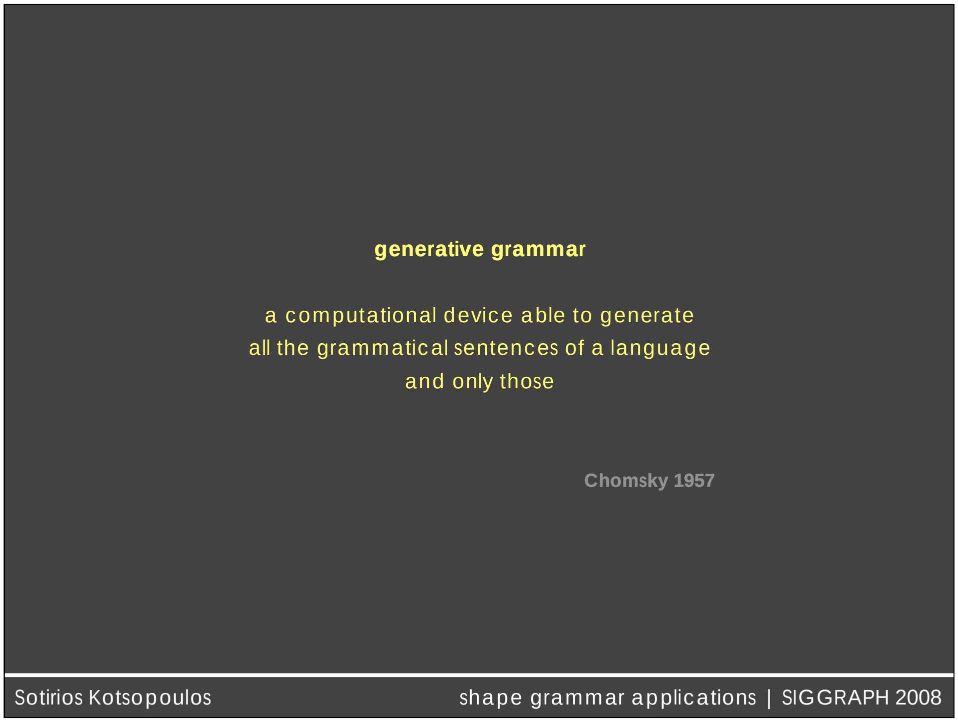
This section includes examples of applications of shape grammars in design education, and practice. The presentation can be divided in three parts: recapitulation, analysis, synthesis.

After a brief recapitulation of the main computational devices of shape grammars, it follows an overview of their applications in the analysis of design languages. Some examples of applications of grammars in the synthesis of new design languages are also presented.



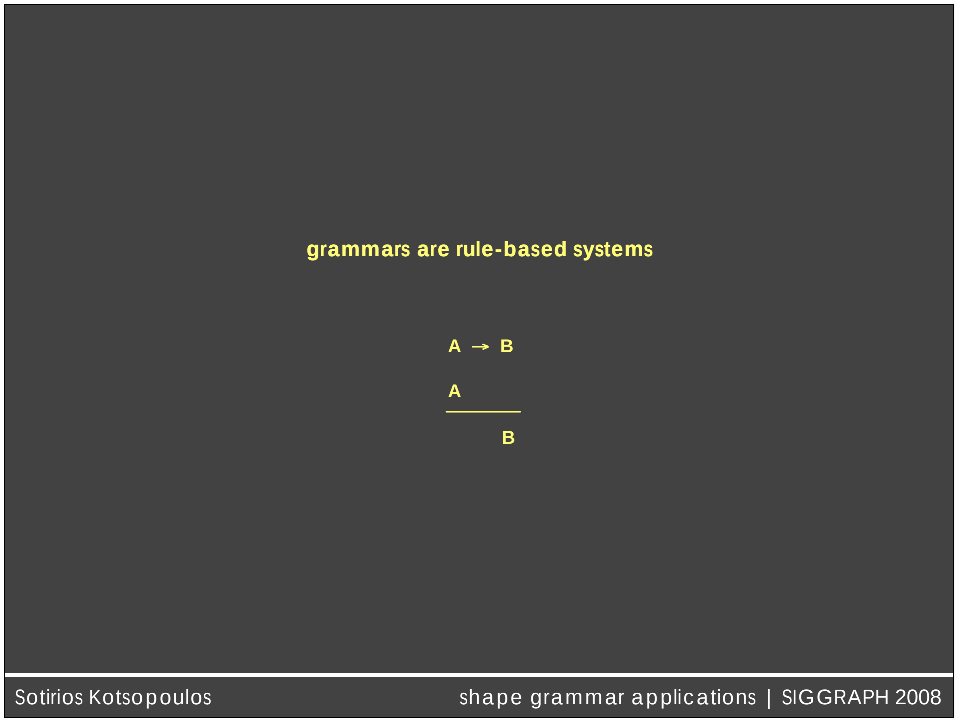
Slide 2

An outline of important developments in the history of computation



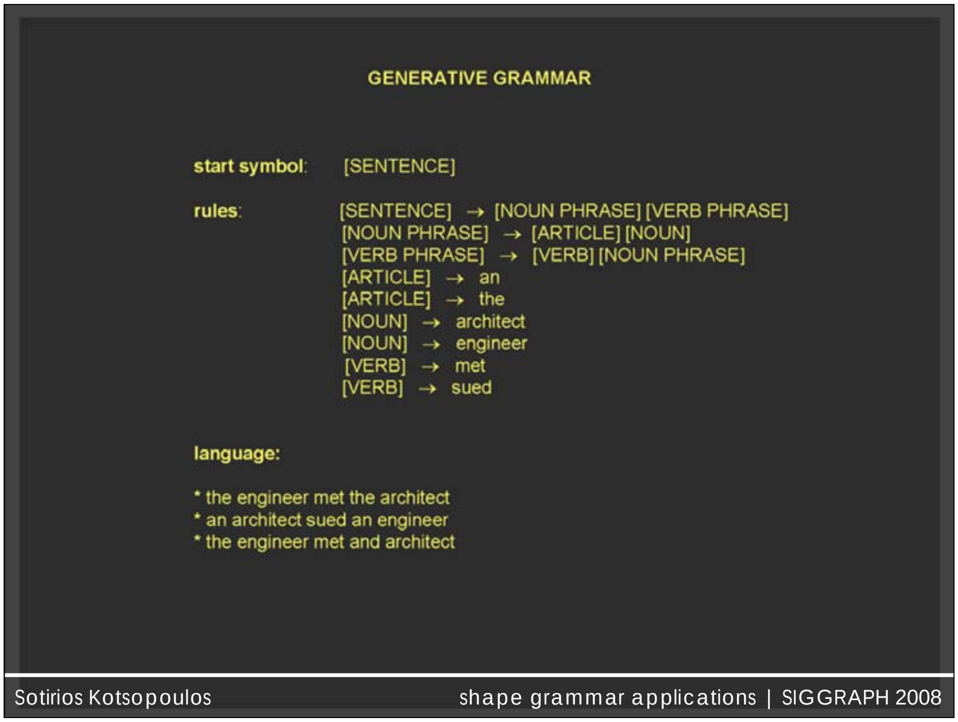
Slide 3

Definition of “grammar” as presented in Chomsky’s *Syntactic Structures* (1957)



Slide 4

Grammars are systems that contain computational rules. In the traditional grammars, the substitution rules are used to erase and rewrite symbols.



Slide 5

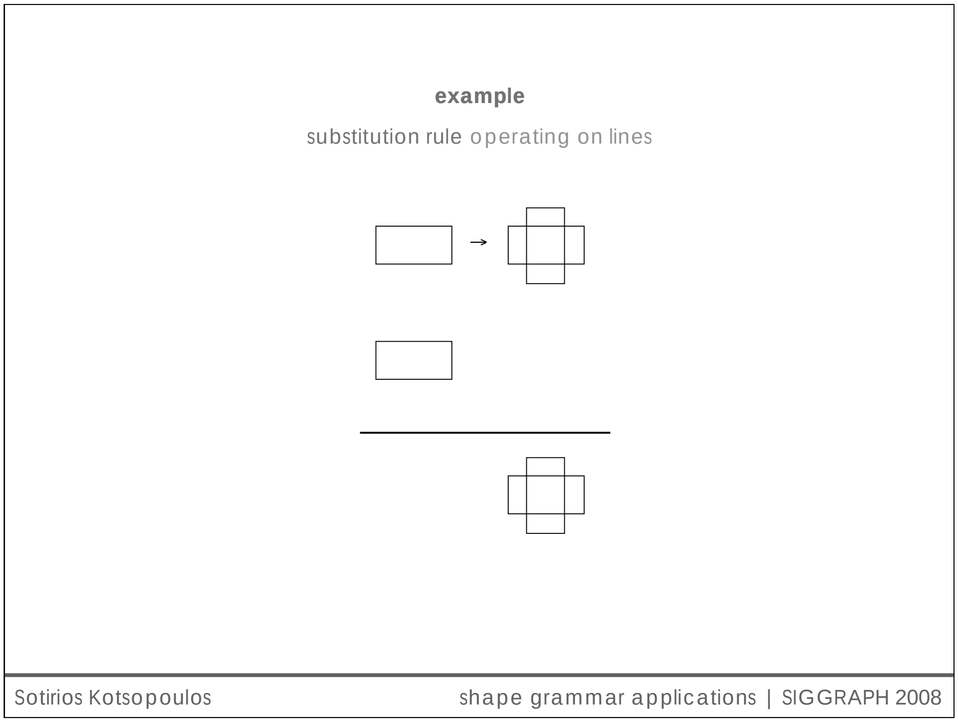
For example the substitution rules of the above example specify the substitutions that are necessary in order to construct a specific set of sentences.

in shape grammars substitution rules

operate on points, lines, planes, solids

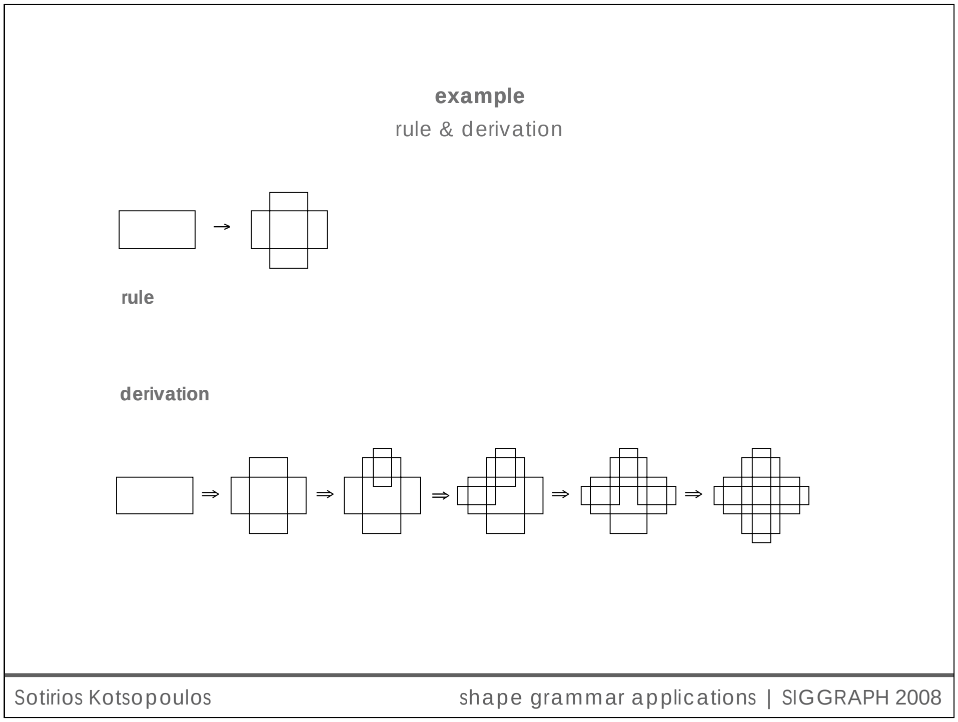
Slide 6

Shape grammars are rule based systems in which substitution rules operate on elements of all spatial dimensions, not just symbols. These elements include points, lines, planes or solids.



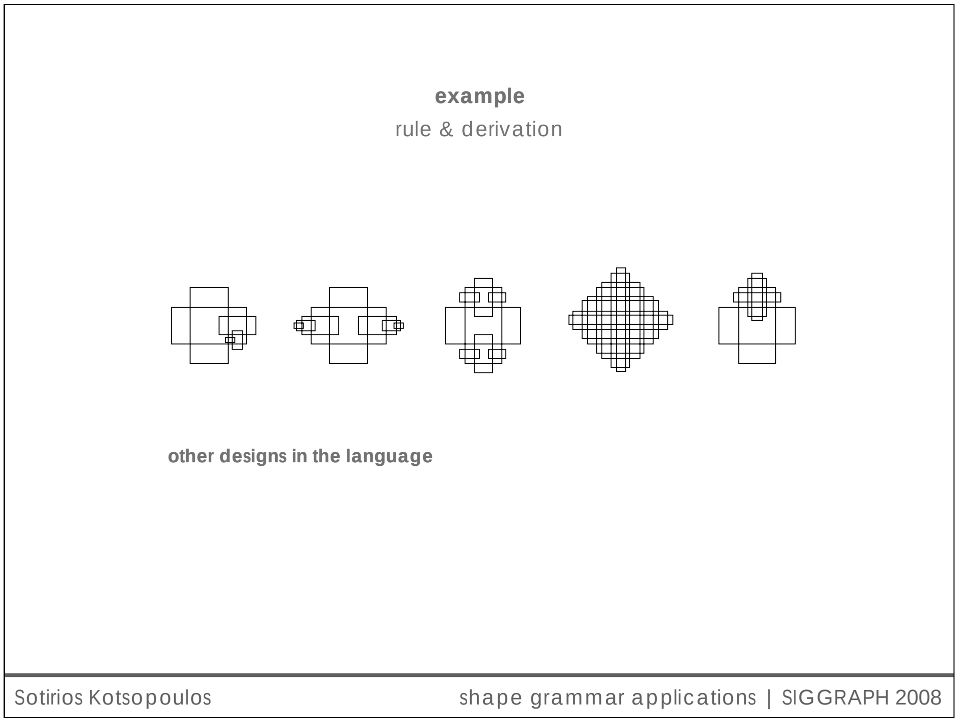
Slide 7

Example of a shape rule applying on shapes made out of lines.



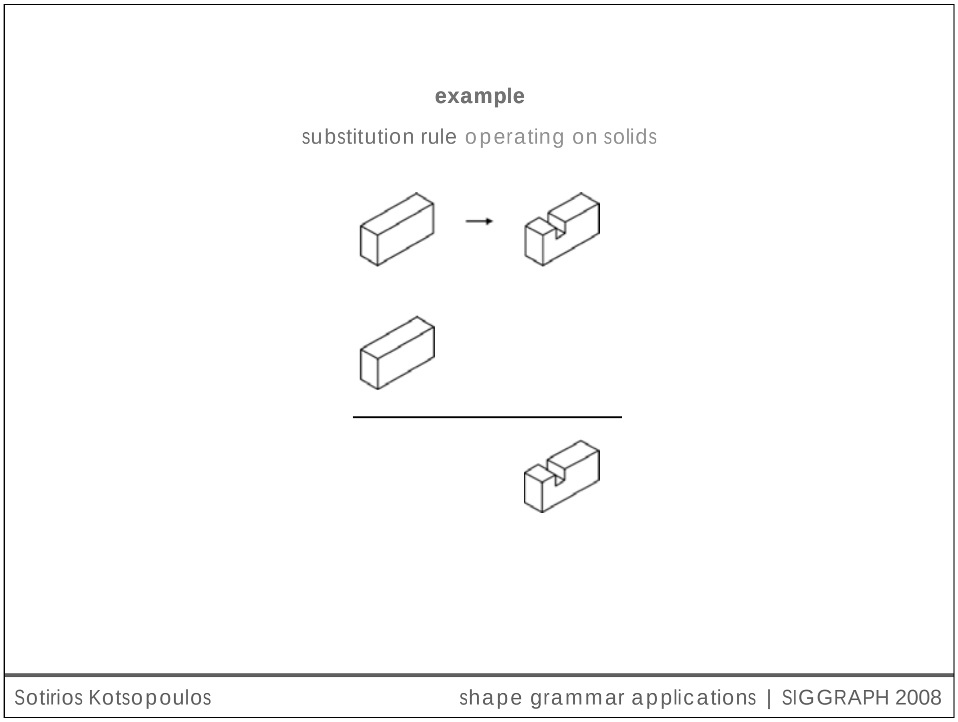
Slide 8

Example of a possible derivation.



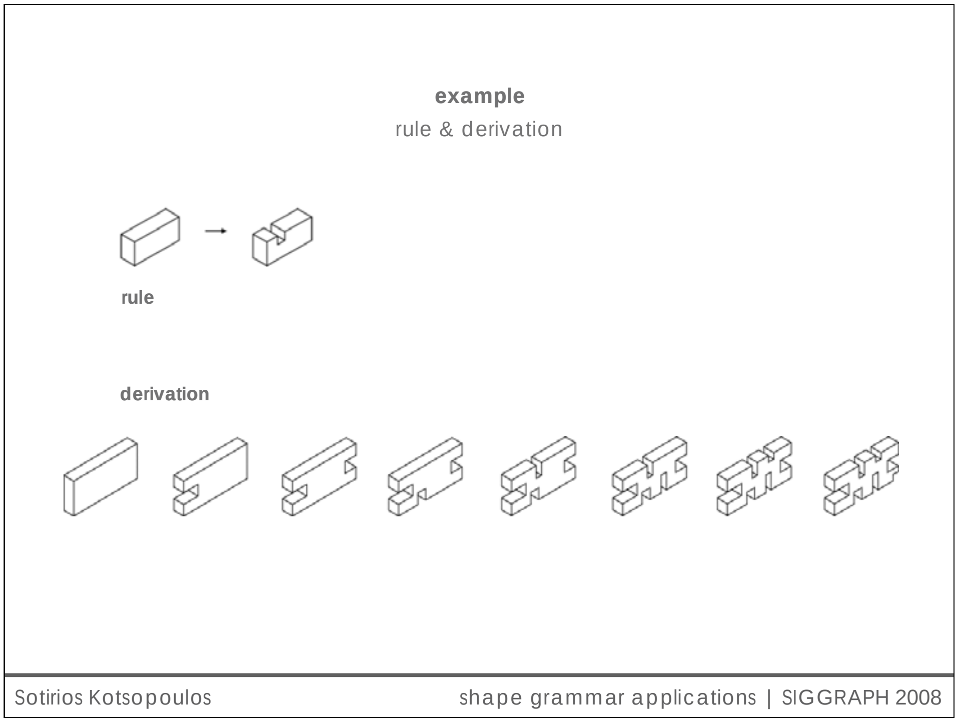
Slide 9

Examples of alterative designs in the same language. These are other possible arrangements belonging to the same set of productions.



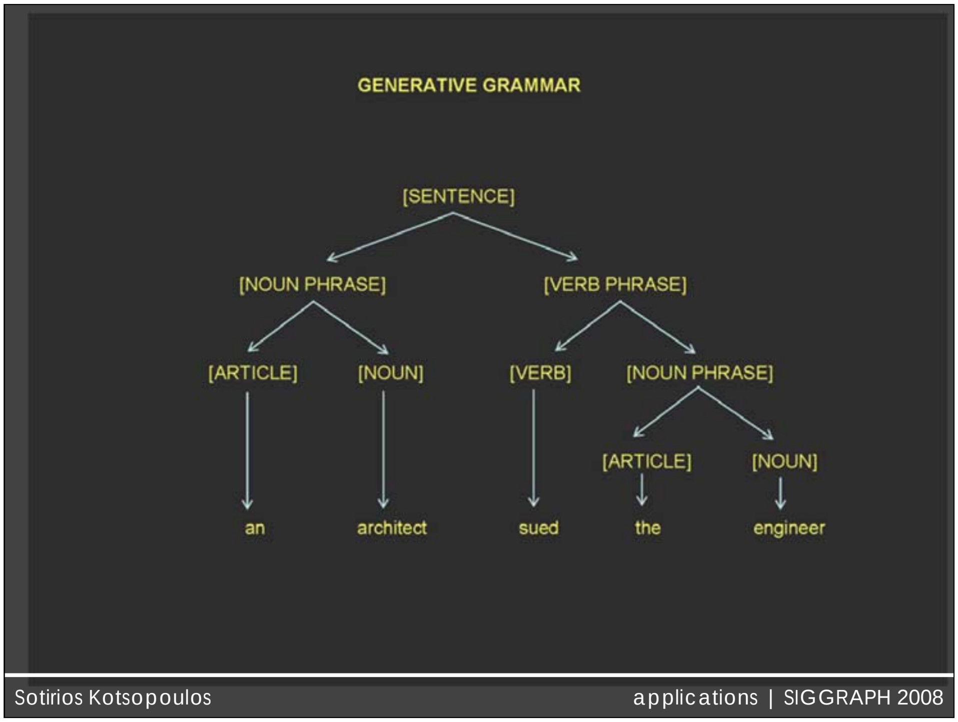
Slide 10

Example of a shape rule applying on shapes made out of solids.



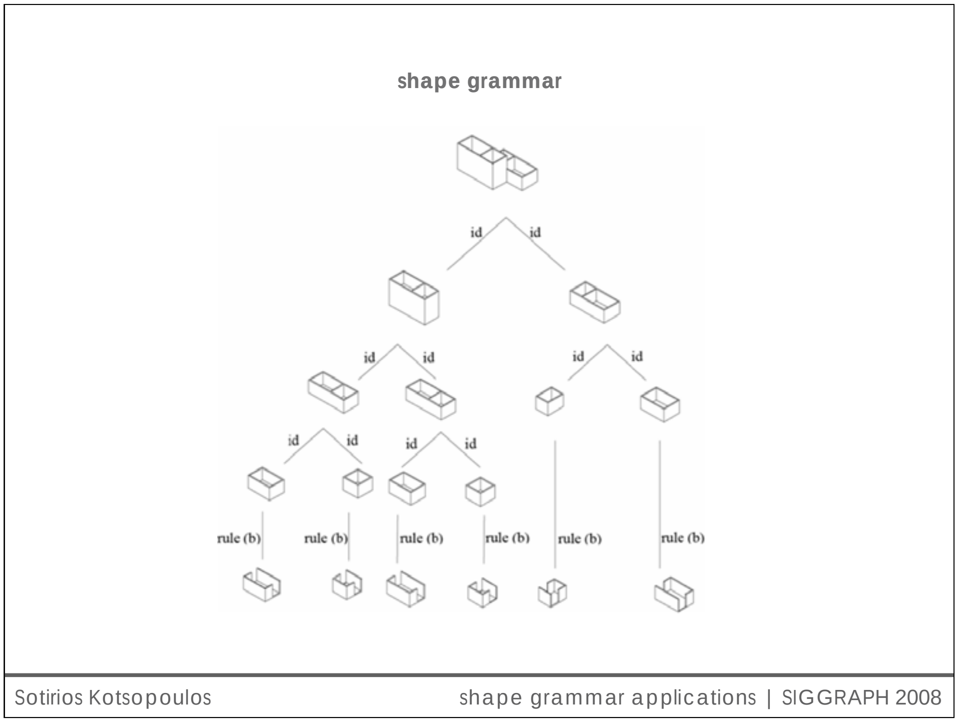
Slide 11

Example of a derivation, after applying the specific rule.



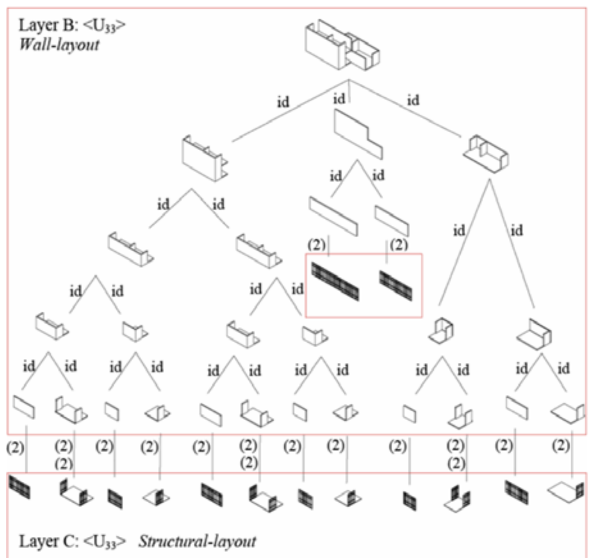
Slide 12

In Linguistics, hierarchies like the above inversed tree are used to illustrate the structure of sentences.



Slide 13

In shape grammars, similar devices can be used at different stages of the design process to illustrate specific properties of a design. These may include general wall layouts, construction details, distribution of openings etc.



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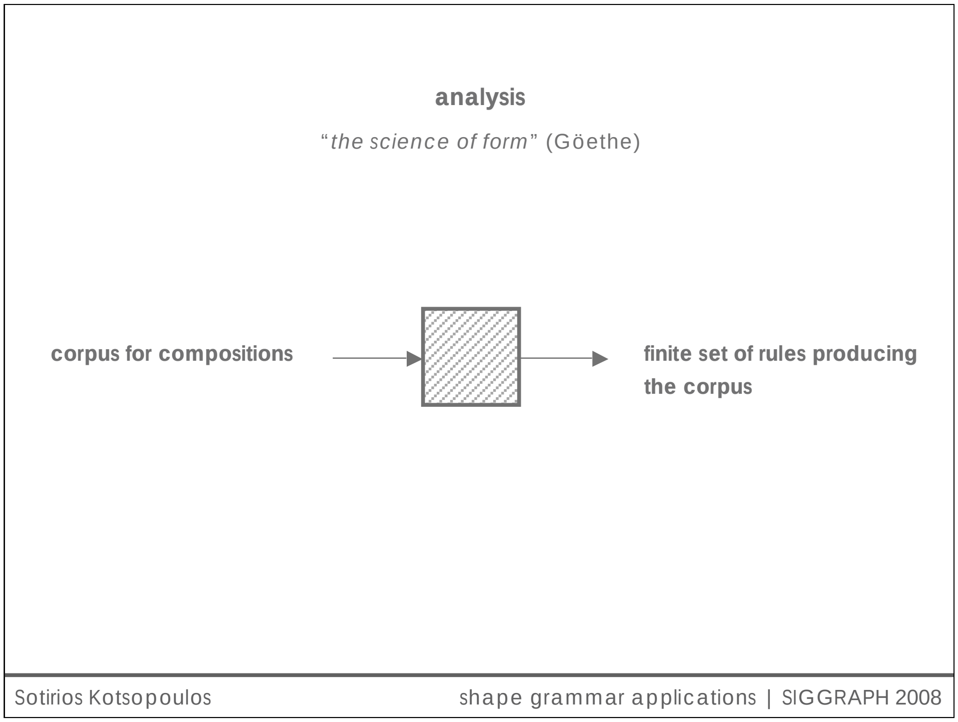
Slide 14

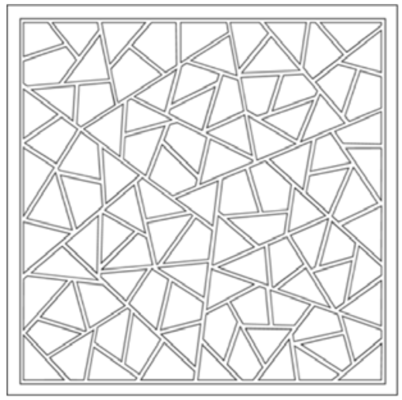
Example of an inversed tree capturing construction details.



Slide 15

The group of examples that follow, concerns the use of shape grammars in the analysis of existing cohesive sets of designs that we call "design languages". Some classic analysis applications and some less known analysis studies are presented in this section.

the Ice-ray Grammar (Stiny 1977)



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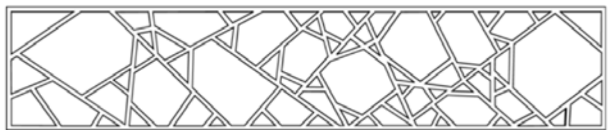
Slide 16

The specific grammatical analysis concerns the generation of highly irregular patterns for ornamental window and grille designs. Parametric shape grammars are defined for the recursive generation of these patterns.

the Ice-ray Grammar (Stiny 1977)



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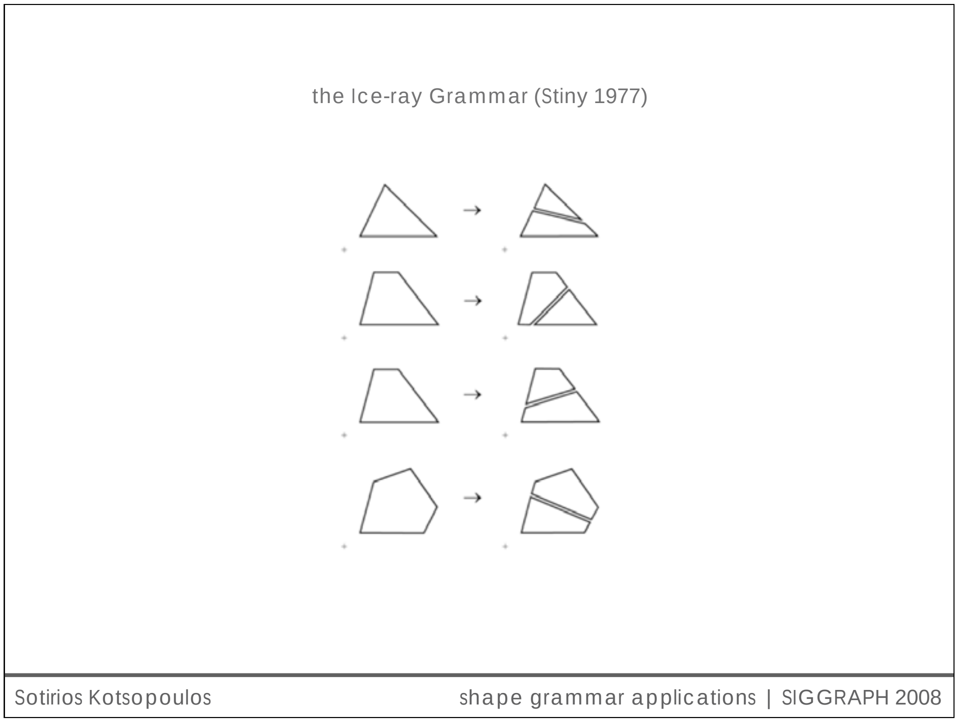
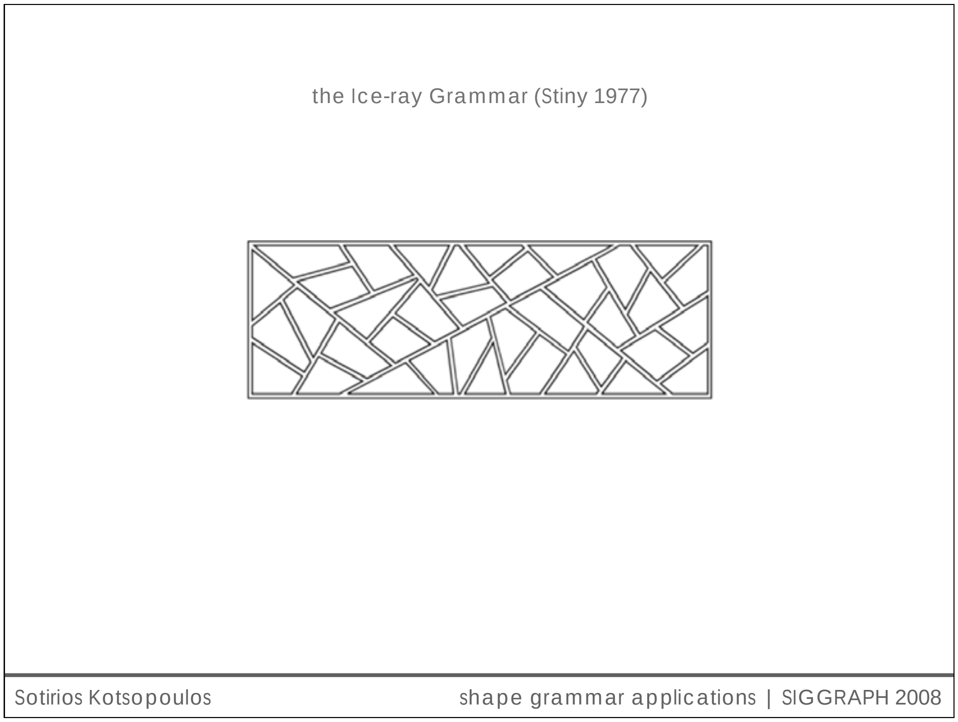
Slide 17

“In the case of the ice ray pattern, [the artisan] divides the whole area into large and equal light spots, and then subdivides until it reaches the size desired; he seldom uses dividers in his work” (Dye, 1949)



Slide 18

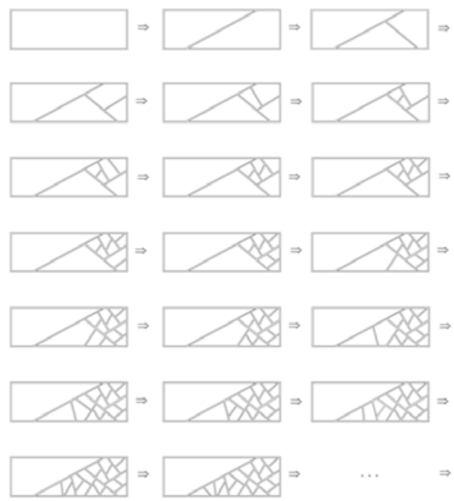
Four dividing rules are used to capture the actions of the artisan. They constitute a shape grammar. The exact divisions are specified by a set of parameters that take into account the ratio of the divided areas



Slide 19

Example of an ice-ray lattice design: Chengtu, Szechwan ice-ray design (1800 AD).

the Ice-ray Grammar (Stiny 1977)



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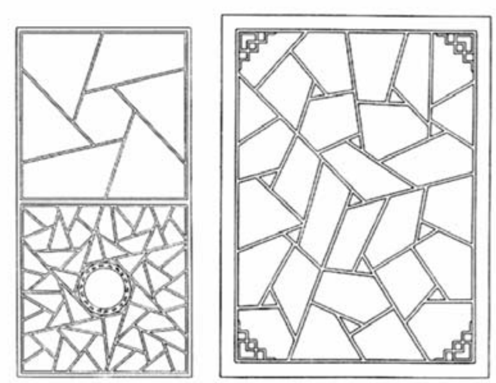
Slide 20

A generation of the previous ice-ray design by means of the shape grammar specified by the four rules.

the Ice-ray Grammar (Stiny 1977)



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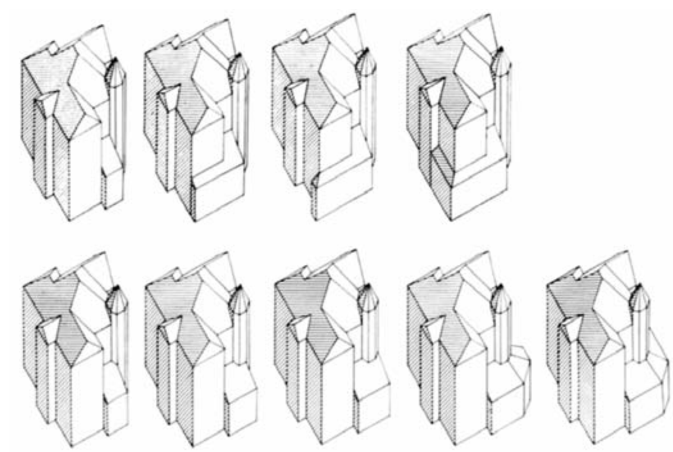
Slide 21

Two more examples of ice-ray lattice designs: Kwanshien, Szzechwan, 1875 AD (left) and Jungking, Szechwan, 1725 AD (right) the Queen Anne Grammar (Flemming 1986)



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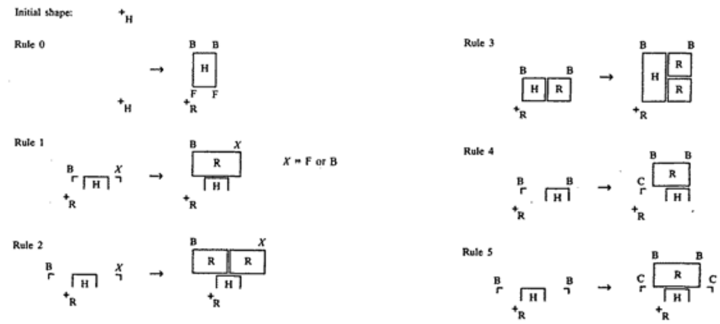
Slide 22

In the specific example, shape grammars are used to determine the generation of Queen Anne style houses, which dominated domestic architecture in the United States in the 1880s. Separate grammars are provided by the author for the generation of plans and for the articulation of plans in three dimensions. The grammars emphasize aspects of geometry and overall design and address how the individual parts and features are related to each other.

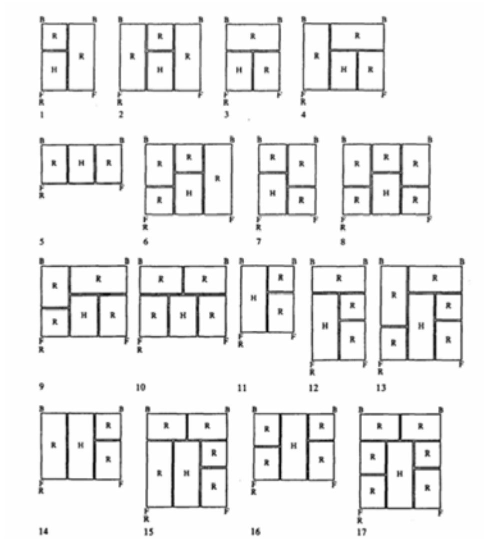
the Queen Anne Grammar (Flemming 1986)



the Queen Anne Grammar: rules generating the basic layout

Slide 23

Initial shape and rules to allocate spaces around hall.



the Queen Anne Grammar: basic layouts generated by the rules 0-3

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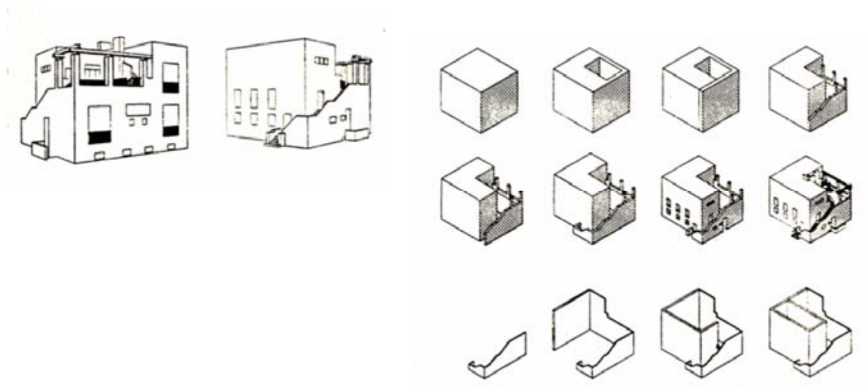
Slide 24

Layouts produced by the application of the rule schemata 0-3 constructive analysis for Loos' house at the Lido (Flemming 1990)



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Slide 25

An introduction to a series of architectural languages characterized by different vocabularies of elements and by grammars whose rules indicate how the elements can be placed in space to form compositions. Exercises with each language include the analysis of precedents; the generation of forms using a given rule set and follow up studies with expanded rule sets. Above an example of a constructive analysis for Loos' house at the Lido.

the Hepplewhite chair Grammar (Knight 1980)

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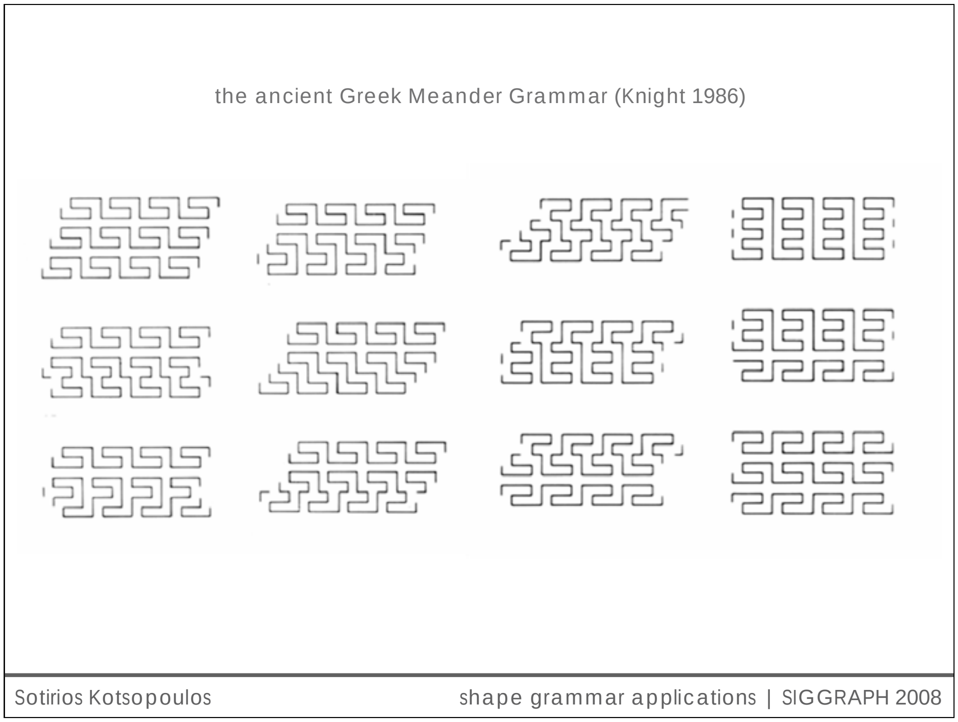
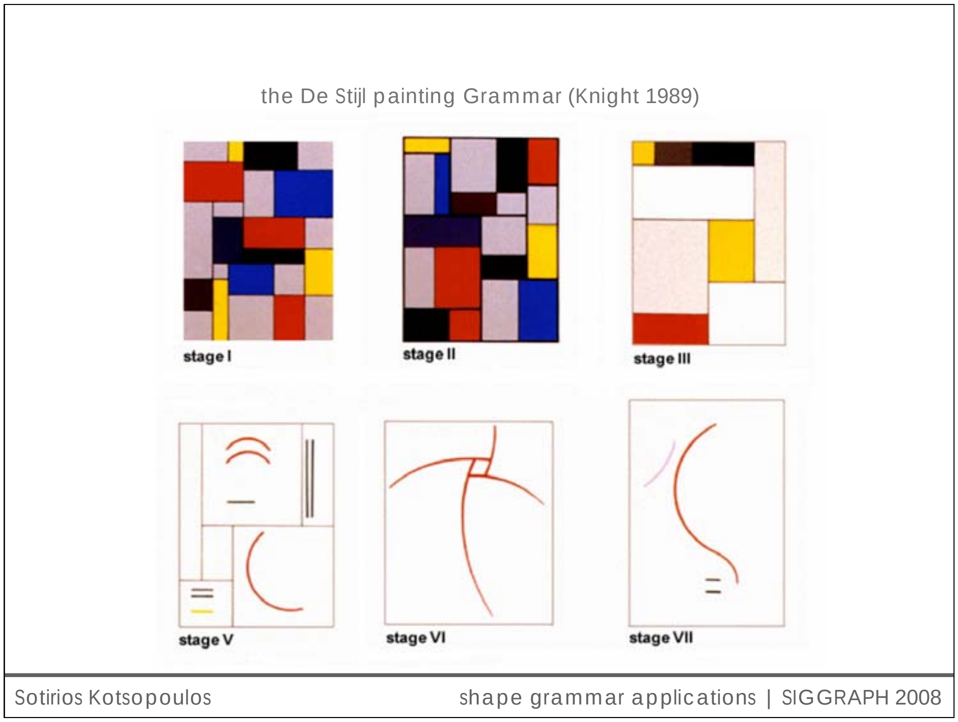
Slide 26

The paper presents a parametric shape grammar for the generation of Hepplewhite-style chair-back designs. Three examples of the style are studied, and in particular the design of the back itself. The proposed parametric shape grammar defines its unique characteristics and constraints. The grammar specifies rule schemata that generate not only the three designs in the original corpus but also a wide range of new designs within the constraints of the paradigm.



Slide 27

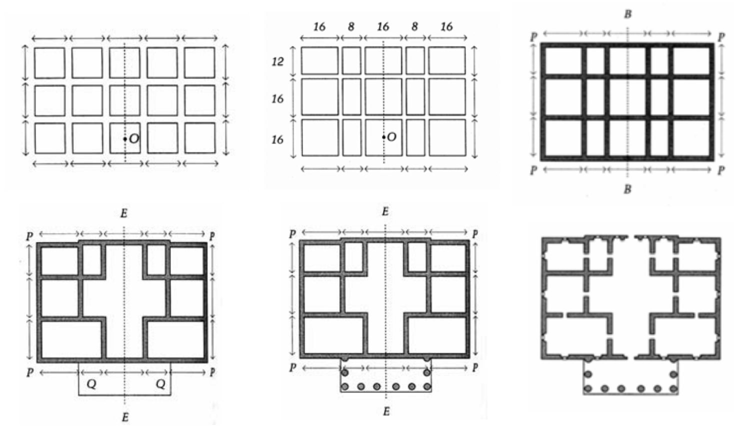
A formal model is applied to describe change in the meanders of the Geometric ancient Greek ornamental style. Shape grammars are used to explicate the underlying design of the meander from its earliest known from to the more complex forms that evolved from it.



Slide 28

The paintings of two artists Georges Vantongerloo and Fritz Glarner are examined and parametric shape grammars are outlined that capture the transformations from one stylistic stage, or grammar, to the next. The rules of each grammar are divided into rules that define relationships between forms or lines, and rules that define relationships between colors. Form rules and color rules are subdivided into categories of form and color rules that have specific compositional functions. The categories allow the rules with similar functions to be compared in different stylistic stages.

the Palladian Grammar (Stiny & Mitchell 1978)



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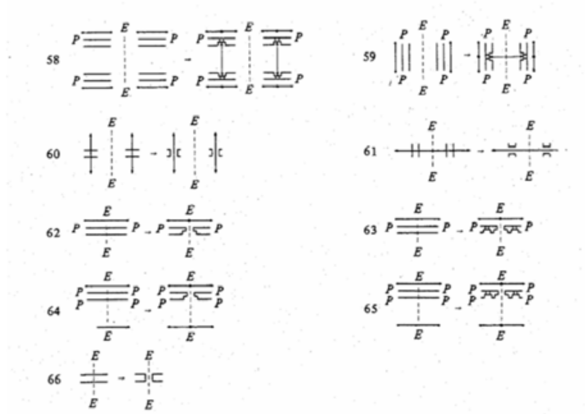
Slide 29

A parametric shape grammar is proposed for the generation of the Palladian villa plans in six steps, including the generation of the grid and of the parti, the wall layout, the organization of the rooms, the addition of the entrance and the arrangement of the openings.

the Palladian Grammar (Stiny & Mitchell 1978)



the Palladian Grammar: enfilade rules

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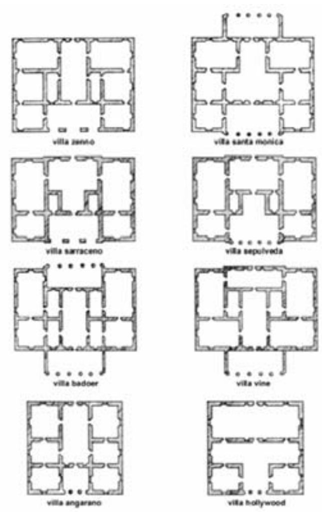
Slide 30

Enfilade rules.

the Palladian Grammar (Stiny & Mitchell 1978)



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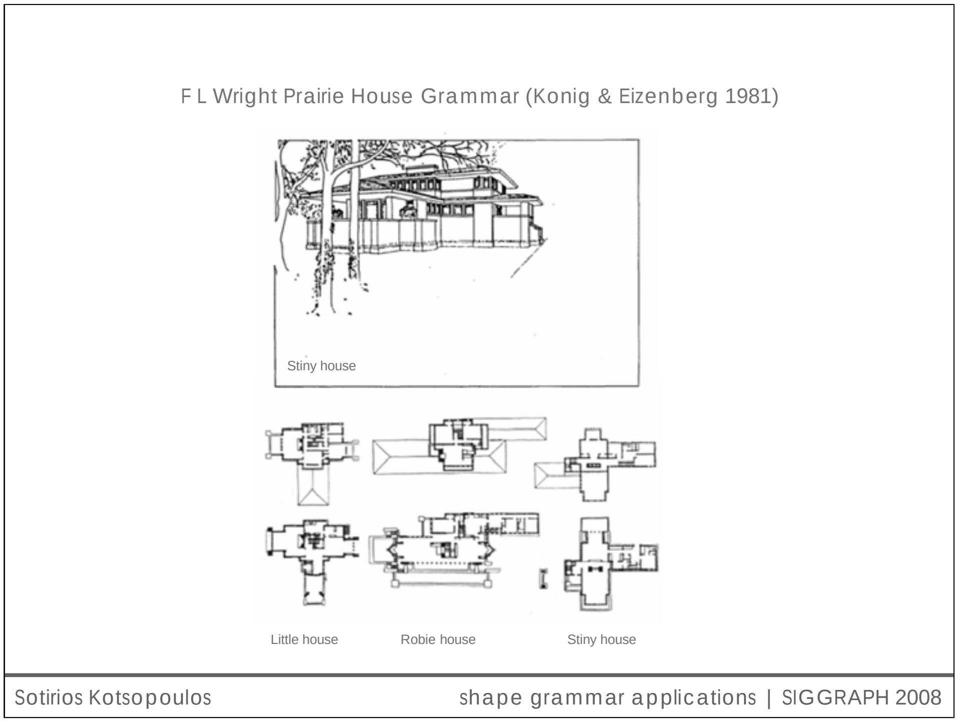
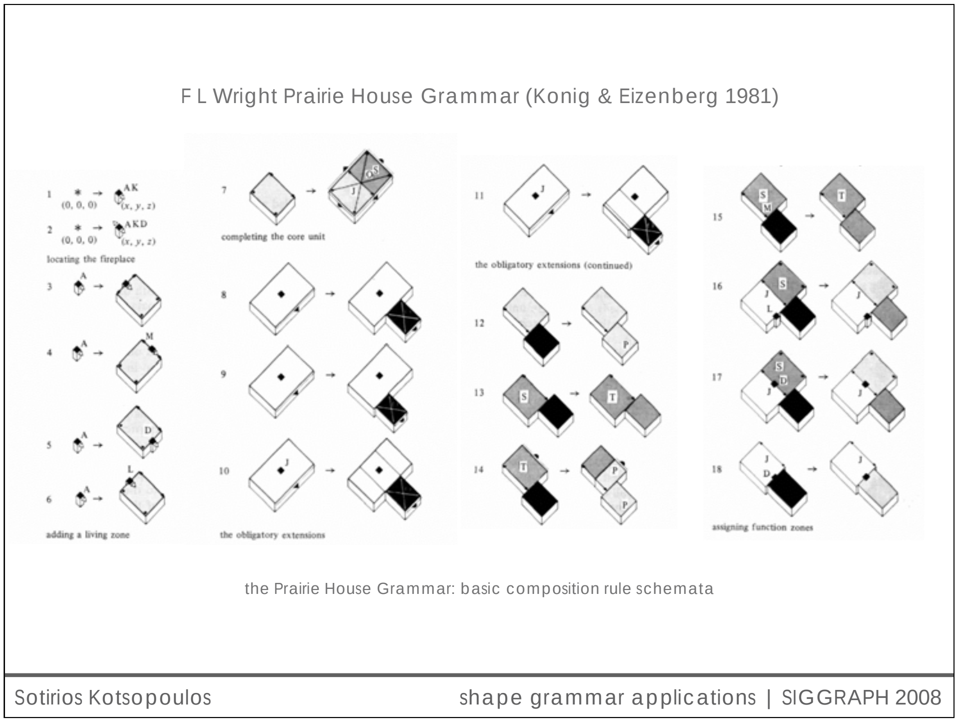
Slide 31

The grammar allows the generation of the original Palladian plans, but also new compositions that follow the compositional restrictions of the original plan arrangements.



Slide 32

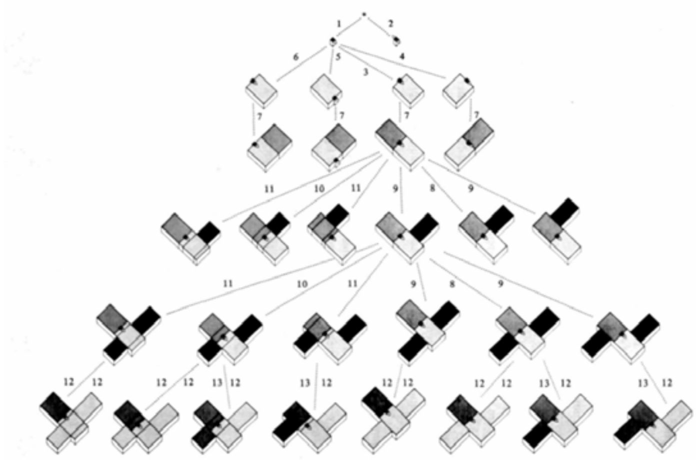
A parametric shape grammar that generates the compositional forms and specifies the function zones of the F. L. Wright's prairie style houses. The establishment of the fire place is the key to the definition of the prairie-style house. Around this fireplace, functionally distinguished blocks are recursively added and interpenetrated to from basic compositions from which elaborated prairie style houses are derived.



Slide 33

Basic composition rule schemata

F L Wright Prairie House Grammar (Konig & Eizenberg 1981)



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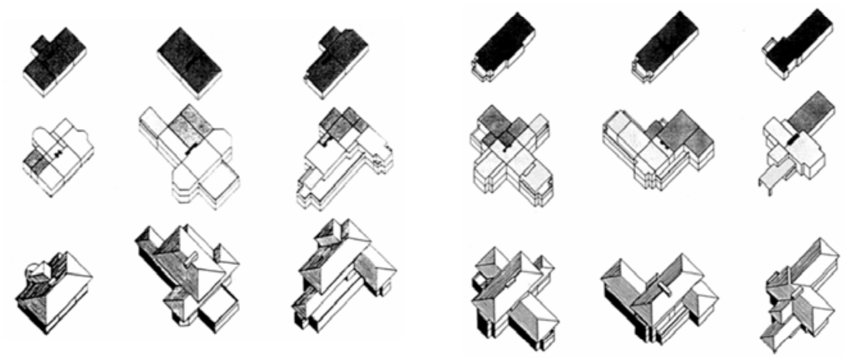
Slide 34

Admissible sequences of shape rule schemata applications that are used to generate basic compositions.

F L Wright Prairie House Grammar (Konig & Eizenberg 1981)



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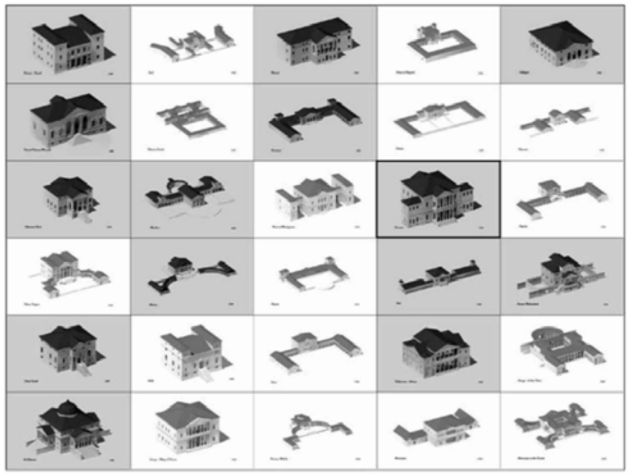
Slide 35

Examples of houses with four functional zones: living, service, porch, bedroom

a Palladian construction grammar (Sass 2007)



the proposed corpus of Palladian villas: darkened images represent built villas

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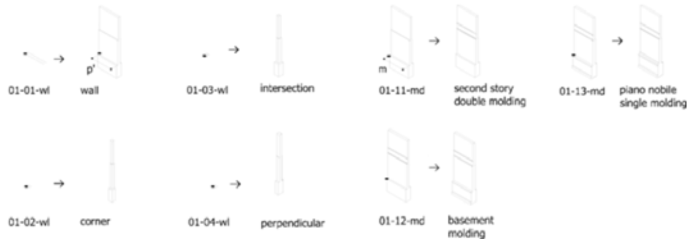
A production system that generates information for physical model manufacture with a 3D-printing device, defined here as a construction grammar. The rules etsbasedon16th-century-masonryconstruction are used to generate a villa model as a 3D construct. The derivation of the grammar demonstrates a design process based on physical constraints as the primary means of grammar structuring. The paper claims that construction rules can be used to build villas in Palladio's corpus, starting with a floor-plan drawing as the initial shape, with little need for an elevation drawing. This paper introduces unexplored issues of physical reasoning in the field of computing and design as part of the rule-building process. As a detailed example, a Palladian villa (the Villa Cornaro) is fabricated as a 3D-printed model from an eleven-part set of rules based on field analysis of Palladio's constructed villas.

a Palladian construction grammar (Sass 2007)



wall rules

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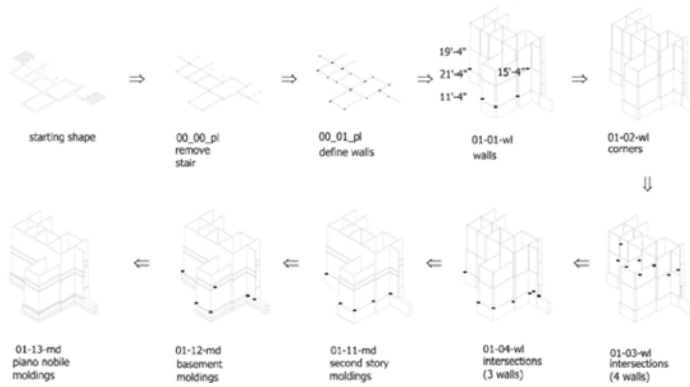
Wall rules.

a Palladian construction grammar (Sass 2007)



wall derivation for the villa Cornaro

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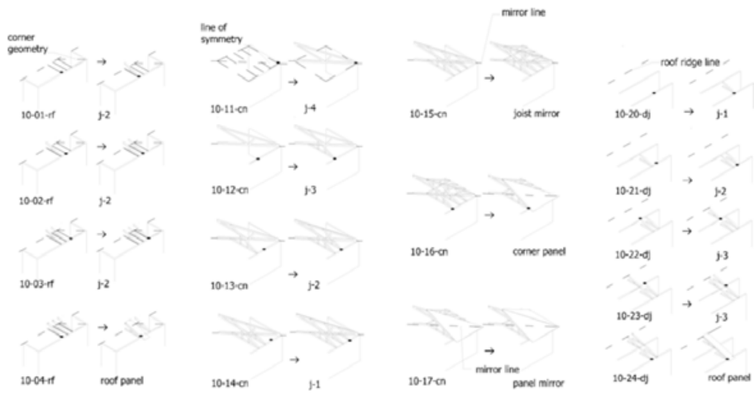
The derivation of wall rules to construct the base of the Villa Cornaro (lower panels).

a Palladian construction grammar (Sass 2007)



roof construction rules

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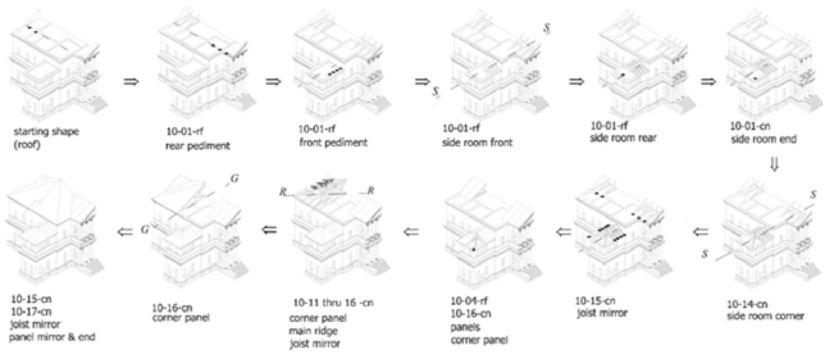
Rules for the construction of the roof

a Palladian construction grammar (Sass 2007)



roof derivation for the villa Cornaro

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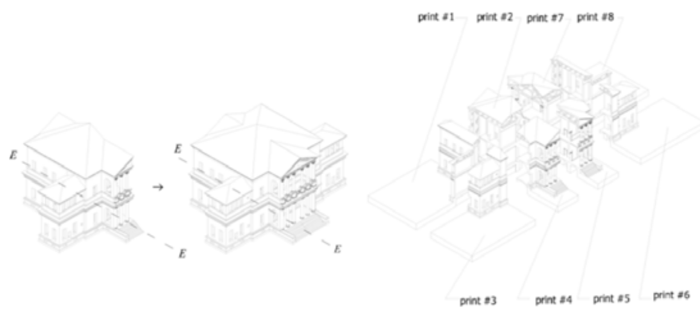
Derivation of the roof

a Palladian construction grammar (Sass 2007)



mirroring the villa along the axis E-E and preparation for 3D printing

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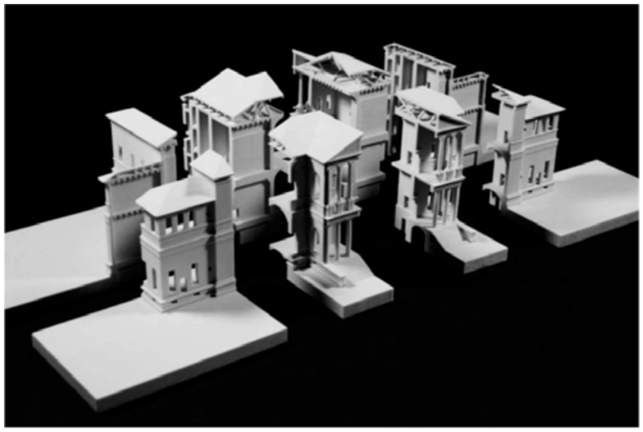
Final rule implementation that mirrors the villa about the axis E-E. Preparation for 3D printing by subdividing the model into eight discrete smaller sections

a Palladian construction grammar (Sass 2007)



final model of the villa Cornaro

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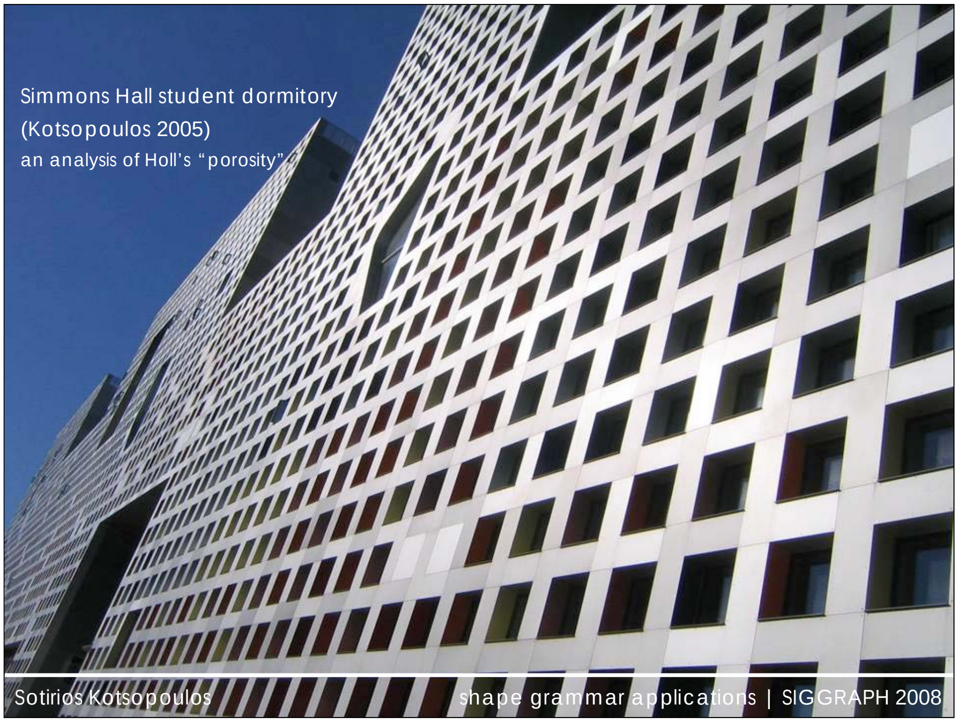
Final 3D model of the Villa Cornaro



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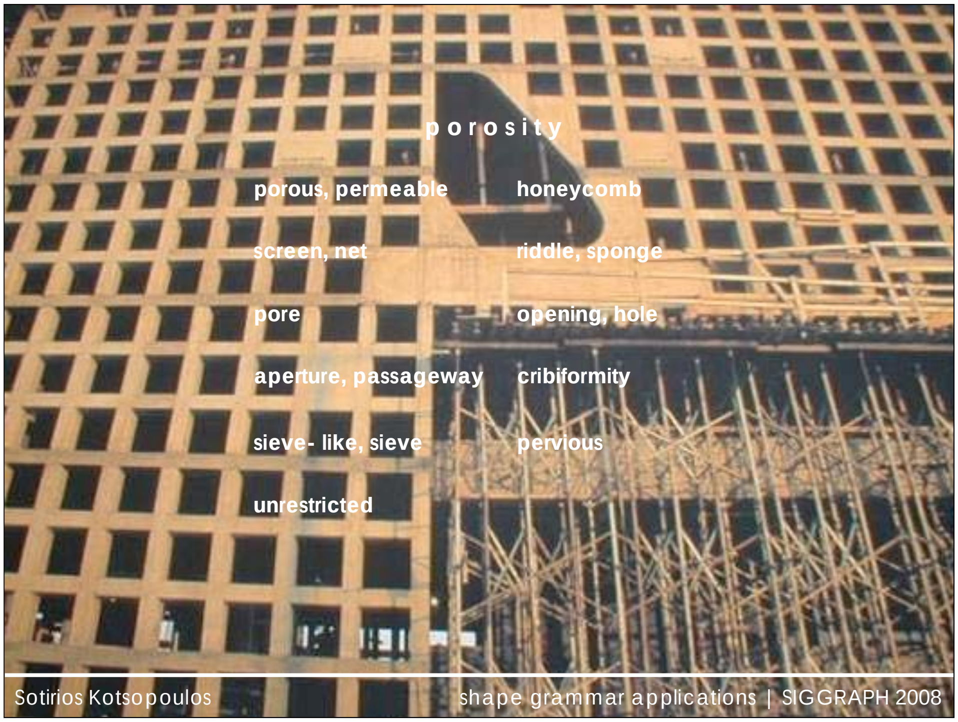
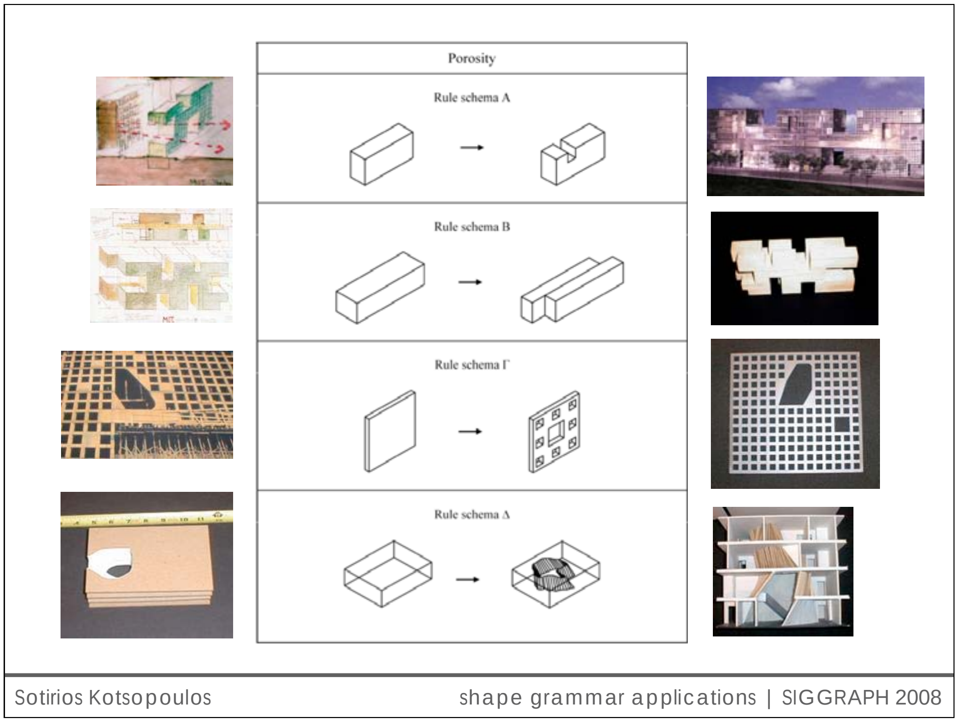
This exercise uses shape rules and grammars in a retrospective analysis that captures the use of the concept of "porosity". Porosity was used as a design concept by architect S. Holl and his team in designing the Simmons Hall student dormitory at MIT campus.



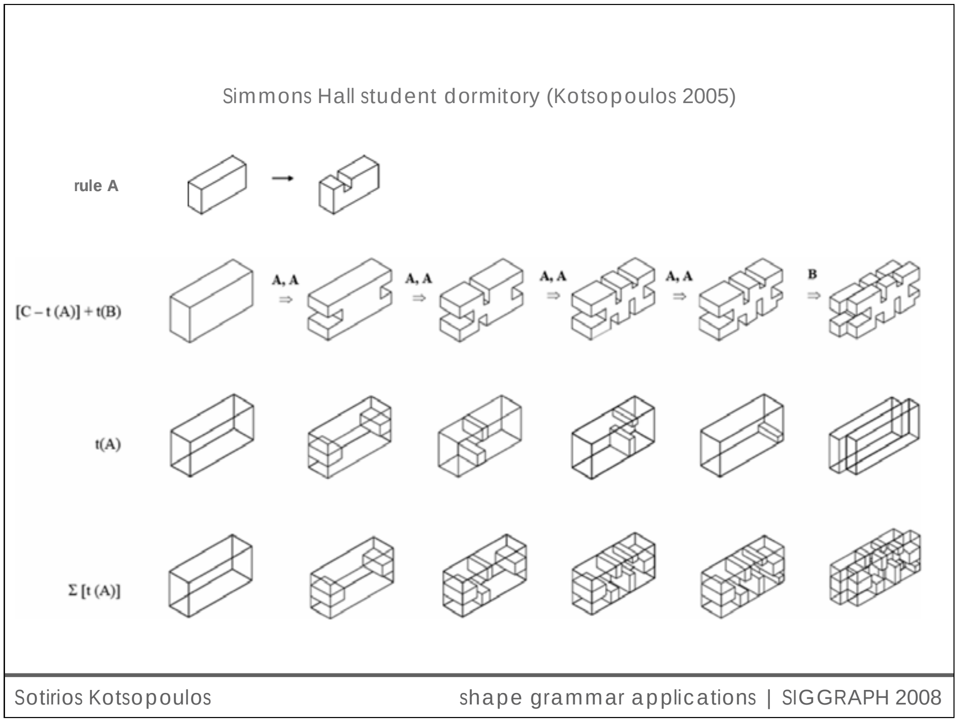
Slide 44

The list of words organized by Holl's design team, in an effort to provide a contextual definition of "porosity".



Slide 45

The design concept of “porosity” introduced specific kinds of design actions that guided the production of drawings, sketches and 3D models in the design studio. These actions are captured above by grammatical rules.

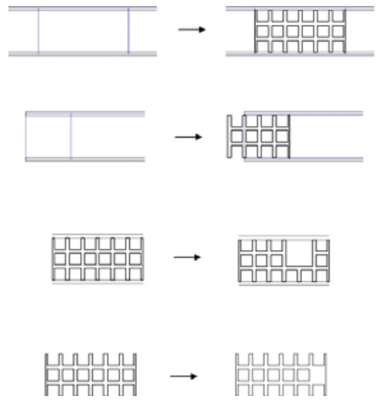


Slide 46

The shape rule schema A appears at the top, in the first row. A possible derivation of the general massing for the building appears in the second row. The third row contains the shape(s) that are subtracted in each step of the derivation.

The third row contains the sum of all the subtracted shapes.

Simmons Hall student dormitory (Kotsopoulos 2005)



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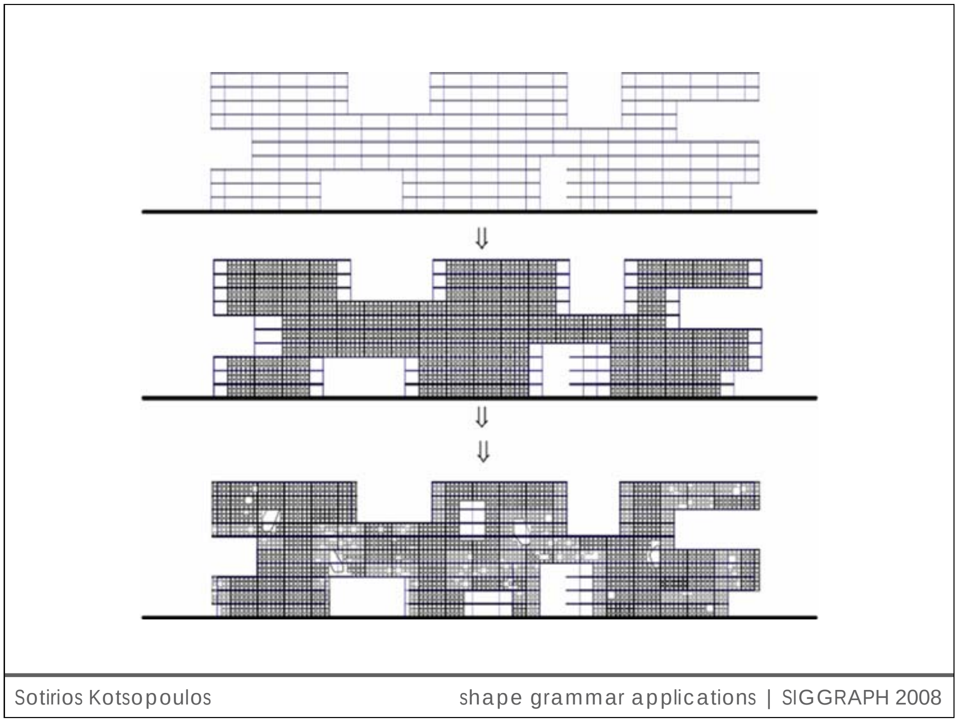
Rule variations of schema Γ that deals with the generation of sieve-like windows on the panels of the elevations, and with their placement on the appropriate positions.



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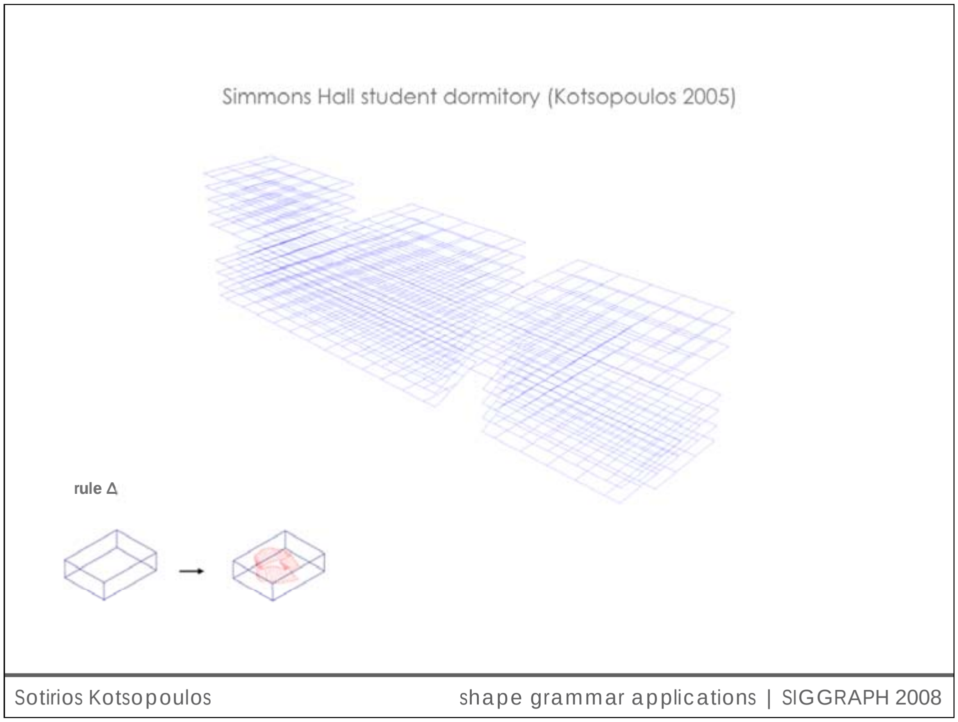
Some steps from the derivation of the elevations according to the previous shape rules.



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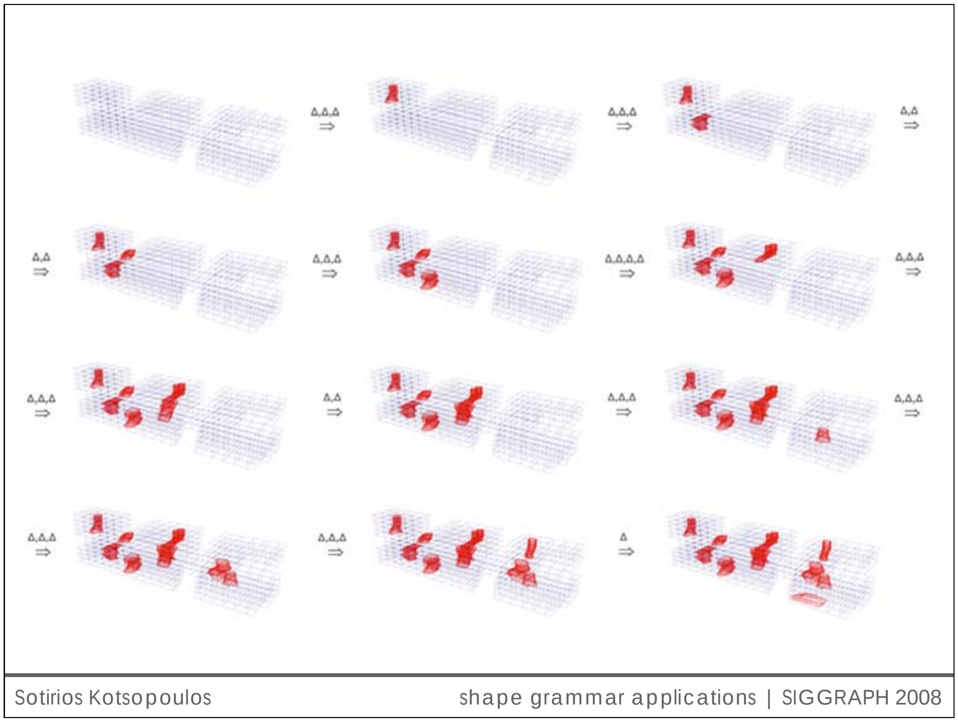
The rule schema Δ is responsible for the generation of the sponge like cavities within the orthogonal grid of the building.

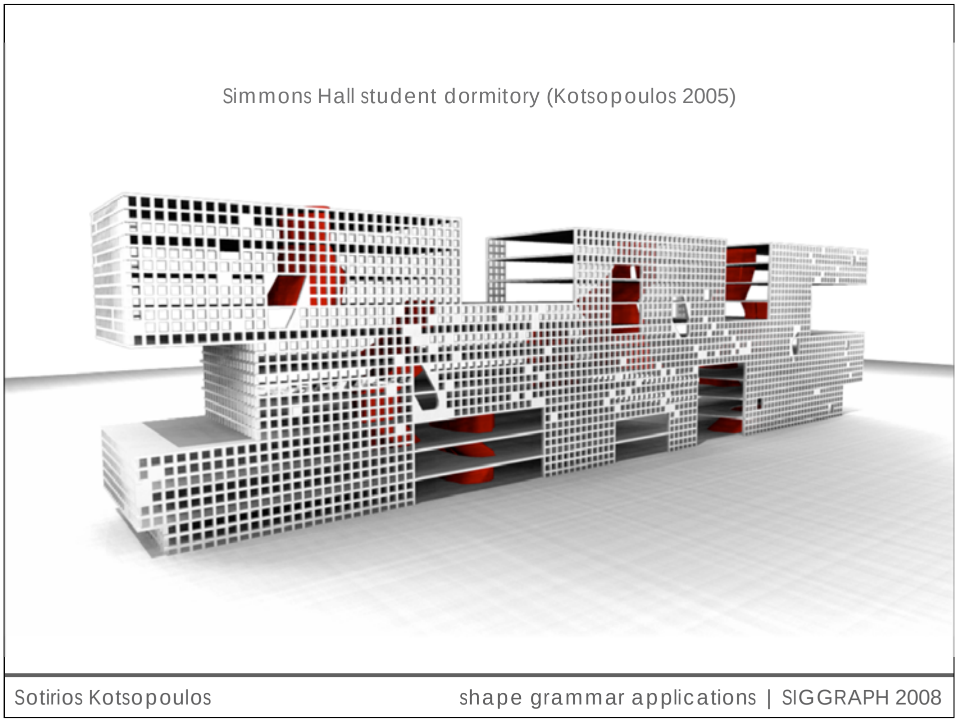


Slide 50

Derivation of the sponge like cavities within the existing orthogonal grid of the building, according to rule schema Δ.

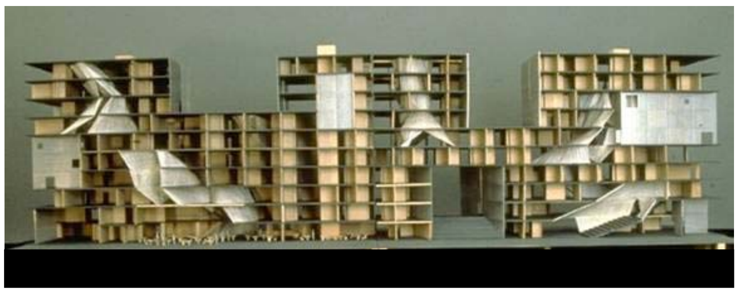
Slide 51

Example of a sponge like cavity at the interior of Simmons Hall.



Slide 52

Example of a possible derivation of Simmons Hall according to the rule schemata Α, Γ, Δ.



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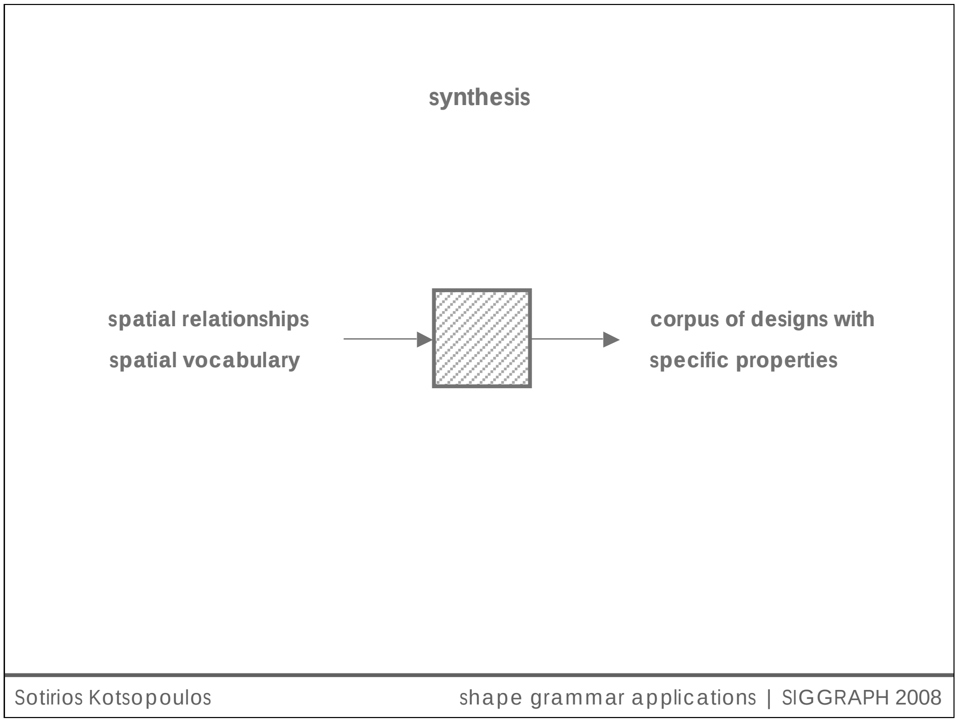
Final implementation of Simmons Hall student dormitory at MIT campus, by S Holl. The bottom illustration presents an much earlier 3D model

Slide 54

An overview of the proposed process: starting from the articulation of possible rules, proceeding to the testing of these rules, and concluding with the organization of non-redundant processes that involve the most effective ones.

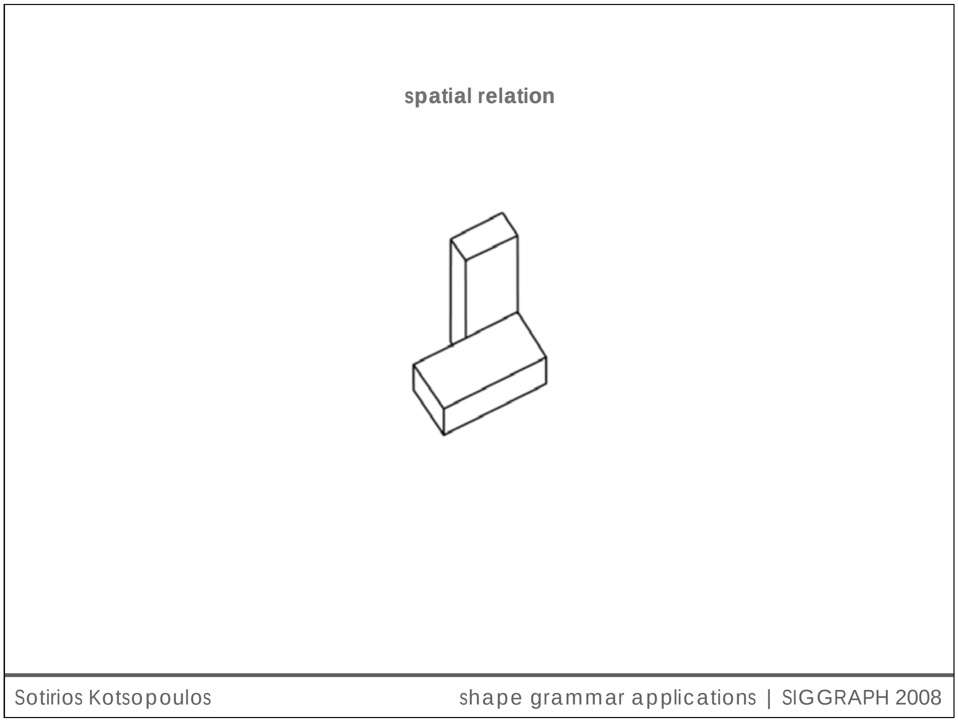


Slide 55

The examples that follow, concern the use of shape grammars in design synthesis, and the construction of new “design languages”.

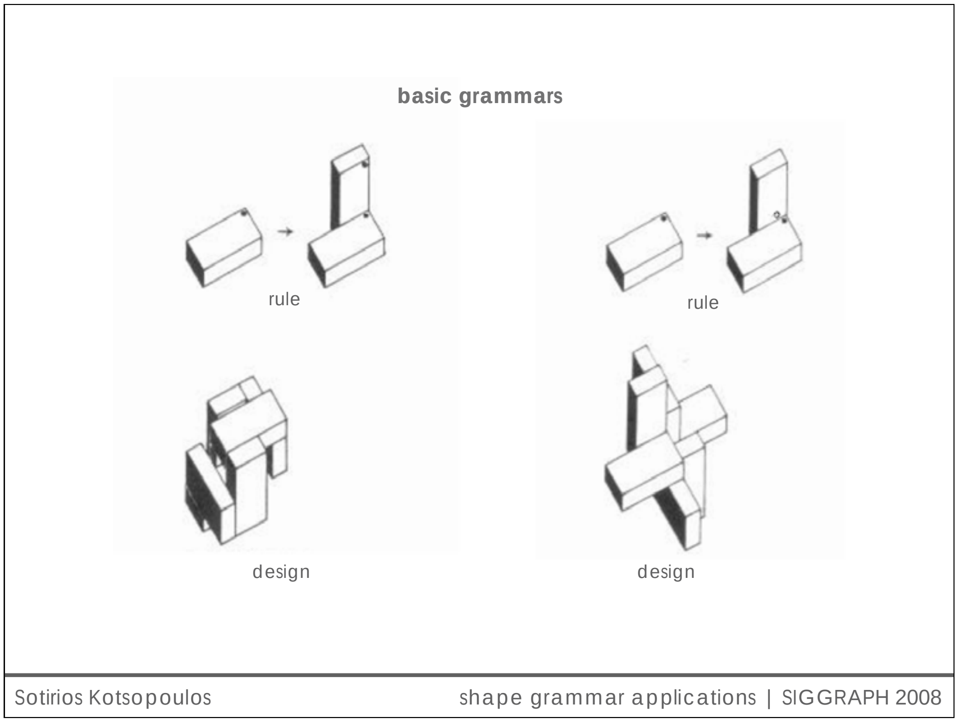
Slide 56

Stiny's Kindergarten grammars draws attention to pedagogical aspects of designing with grammars and rules. In this early application of grammars is outlined for the first time a constructive approach to the notion of the "languages of designs". Froebel's building gifts are used to illustrate the approach.



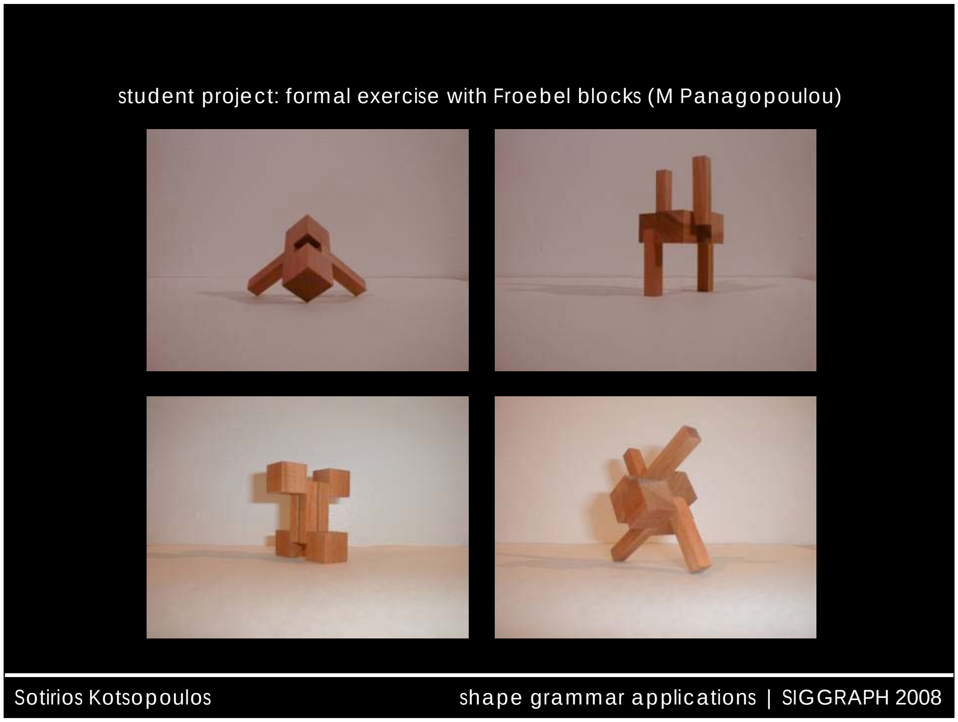
Slide 57

Froebel gifts were used for educational purpose in exercises with grammars. The exercises start with the introduction of a spatial relationship between two forms. Then, the articulation of the corresponding shape rules allows the production of alternative configurations, while taking into account the symmetry properties of the two participating shapes.



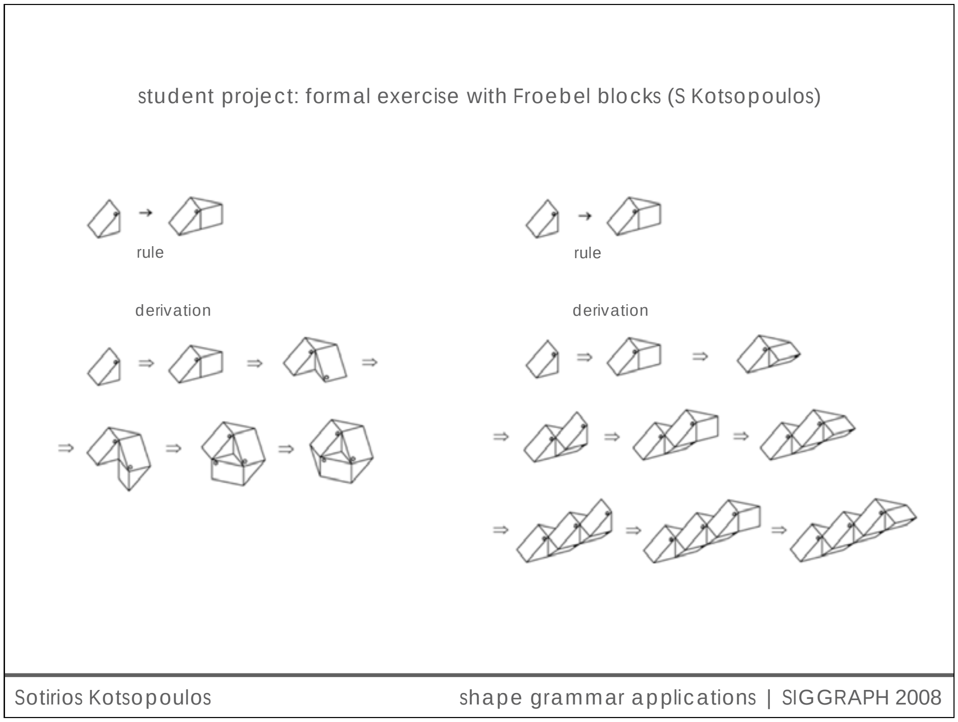
Slide 58

Examples of rules and possible designs are presented above. The symmetry of the participating forms is reduced with the use of labels.



Slide 59

Example of formal exercise with Froebel blocks (cube and oblong). The exercise begins with the definition of a spatial relationship between the cube and the oblong, and the articulation of the corresponding shape rules. Designs are produced by applying the rules, while taking into account the symmetry properties of the two shapes. The exercise was given in the Introduction to Computational Design I: Theory and Applications, taught by Prof. Knight in the Fall of 1998, at the Massachusetts Institute of Technology. Student M. Panagopoulou.

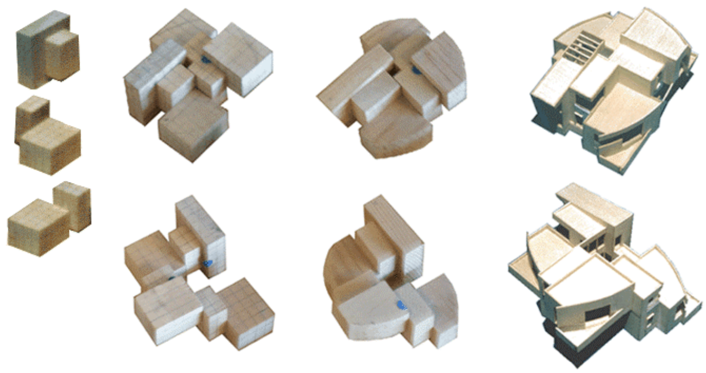


Slide 60

Another example of formal exercise with Froebel blocks (two half cubes).

Student S. Kotsopoulos.

student project: courtyard houses in Malibu, CA, (Jin-Ho Park)



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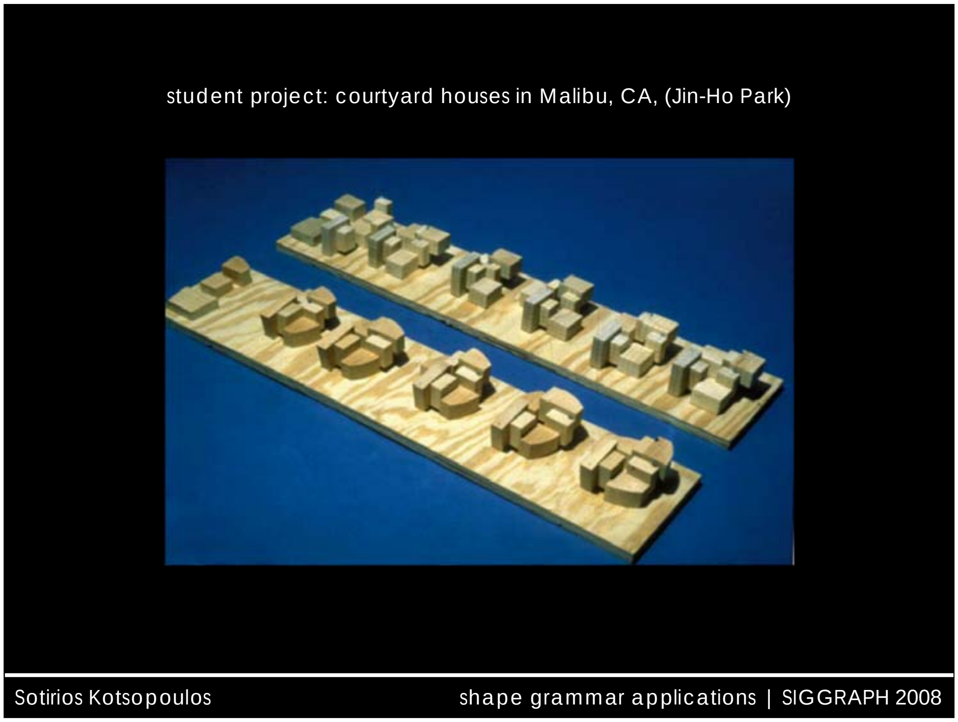
The design of courtyard house in Malibu. The composition begins with the definition of a spatial relationship between the participating shapes (left), and the articulation of the corresponding shape rules. Several compositions are produced by applying the rules. The above designs were developed in the Introduction to Computational Design I: Theory and Applications, taught by Prof. Knight. Student Jin-Ho Park.



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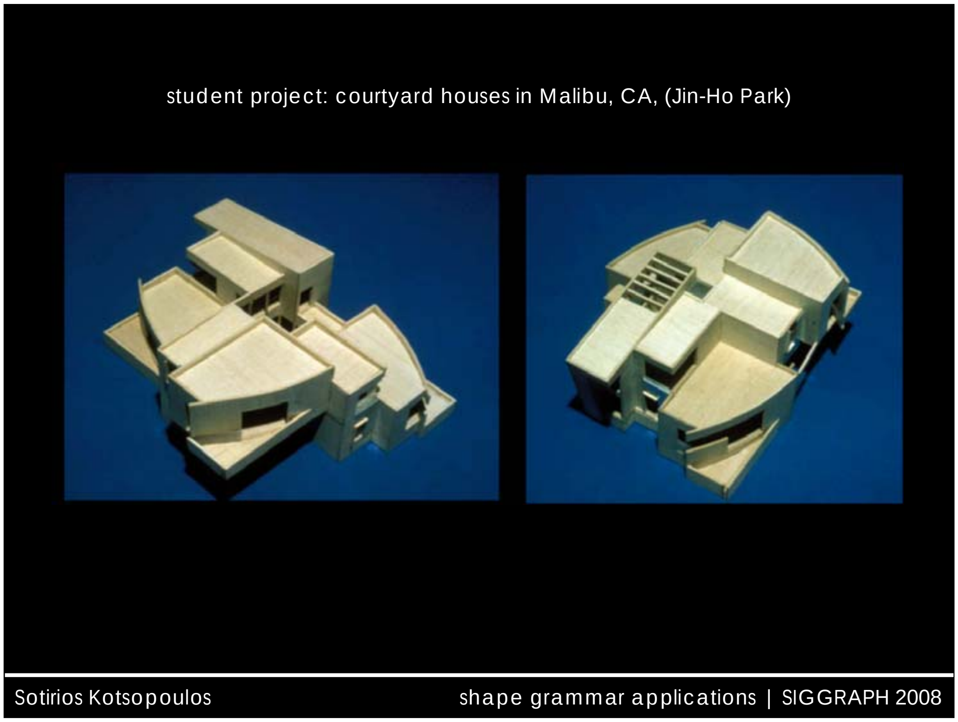
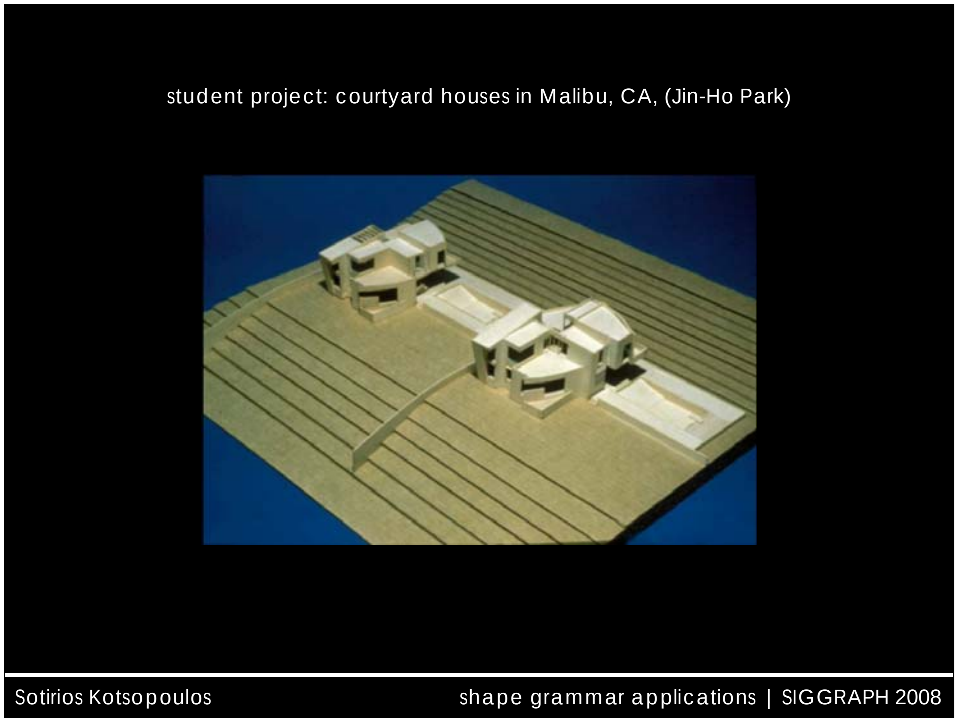
Variations on the same theme, for the courtyard house in Malibu.



Slide 63

Two of the generated designs, constructed in larger scale.



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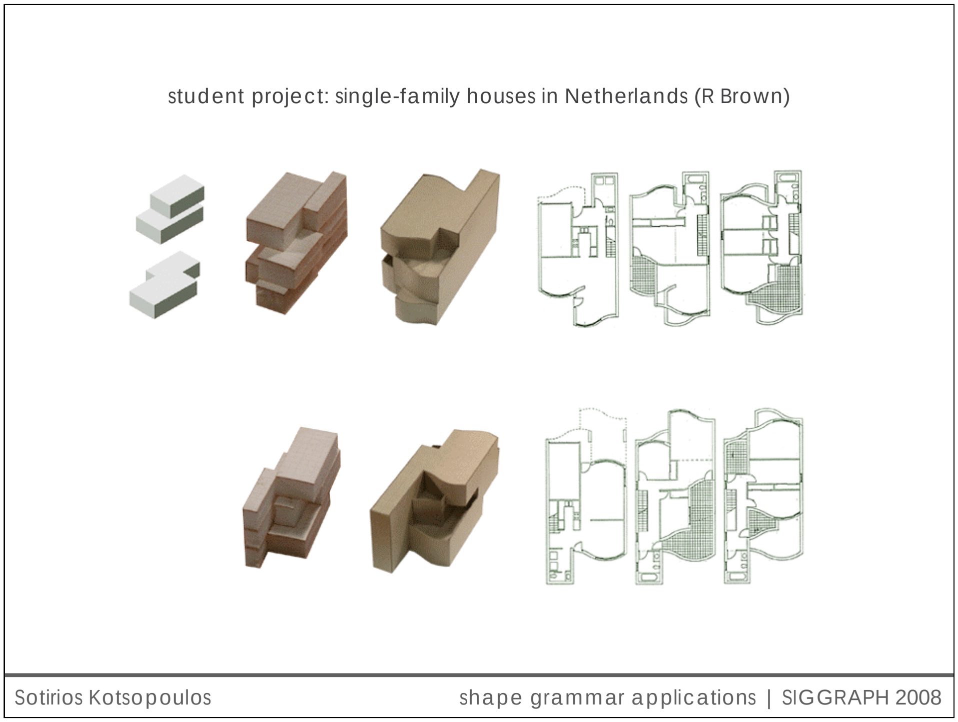
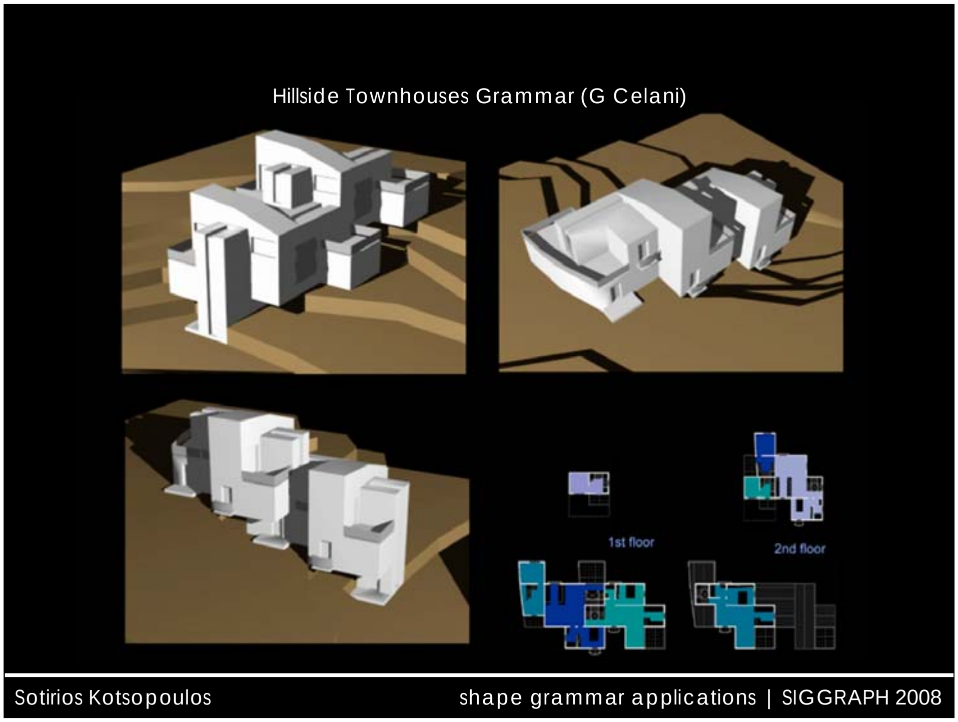
The two selected designs placed at the site.



Slide 65

Another studio example in formal composition: designs for single-family houses in Netherlands. Again, the composition begins with the definition of spatial relationships among forms (left), and the articulation of corresponding rules. Several variations are produced by applying the rules. Student R. Brown



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Another studio example in composition with grammars: designs for Townhouses.

A. Siza's Housing Grammar for Malagueira (Duarte 2005)

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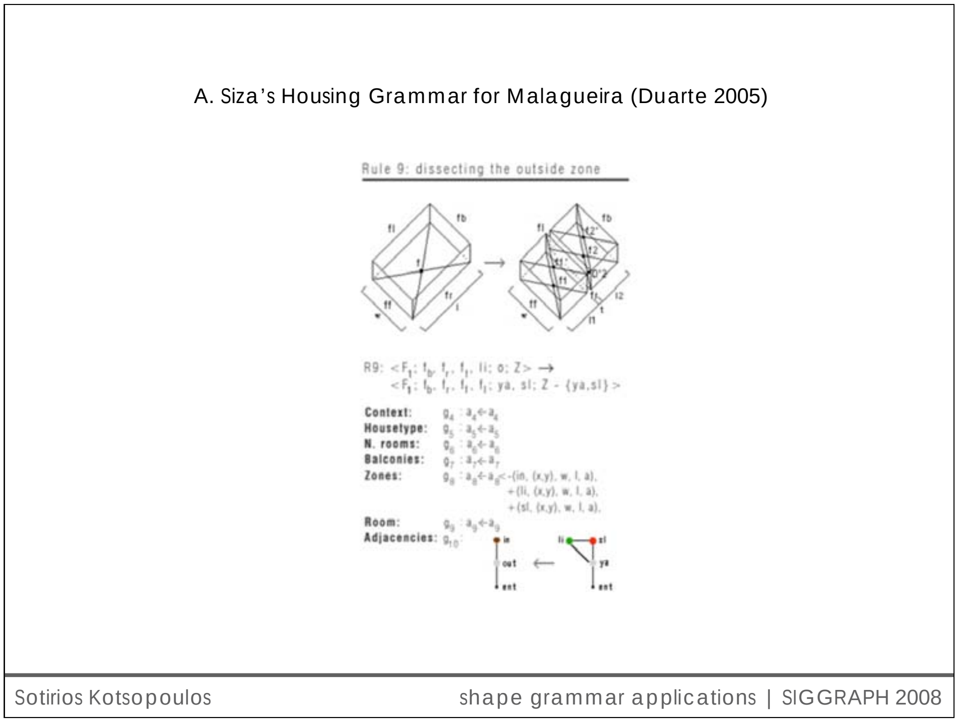
The Malagueira grammar was constructed as an analysis tool, in an effort to capture the original language of A Siza's designs for low cost housing. But the research had also a strong synthesis component as it was intended to expand the initial design language without betraying the spirit of the initial designs.



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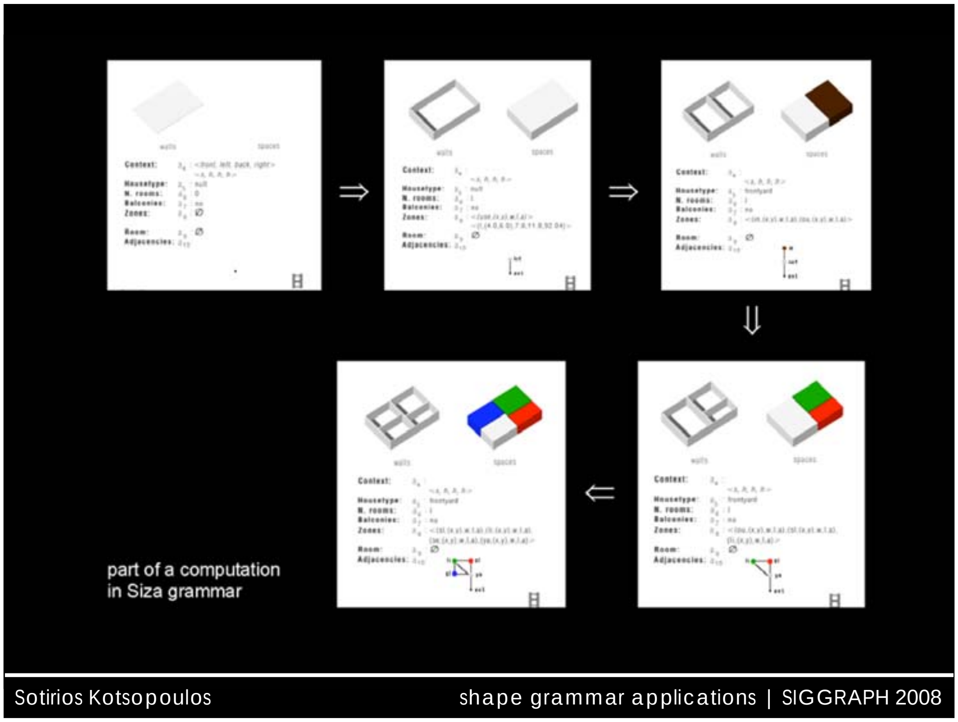
A parametric dissection rule that was used in the grammar.



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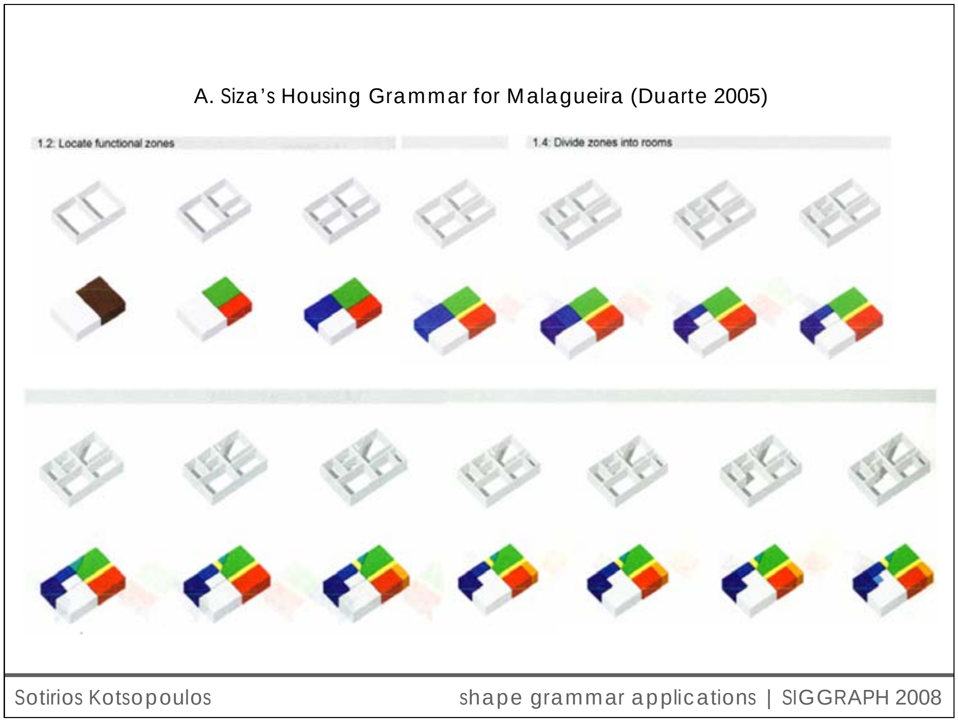
The dissections of rooms and the organization of the different functional zones of the house.



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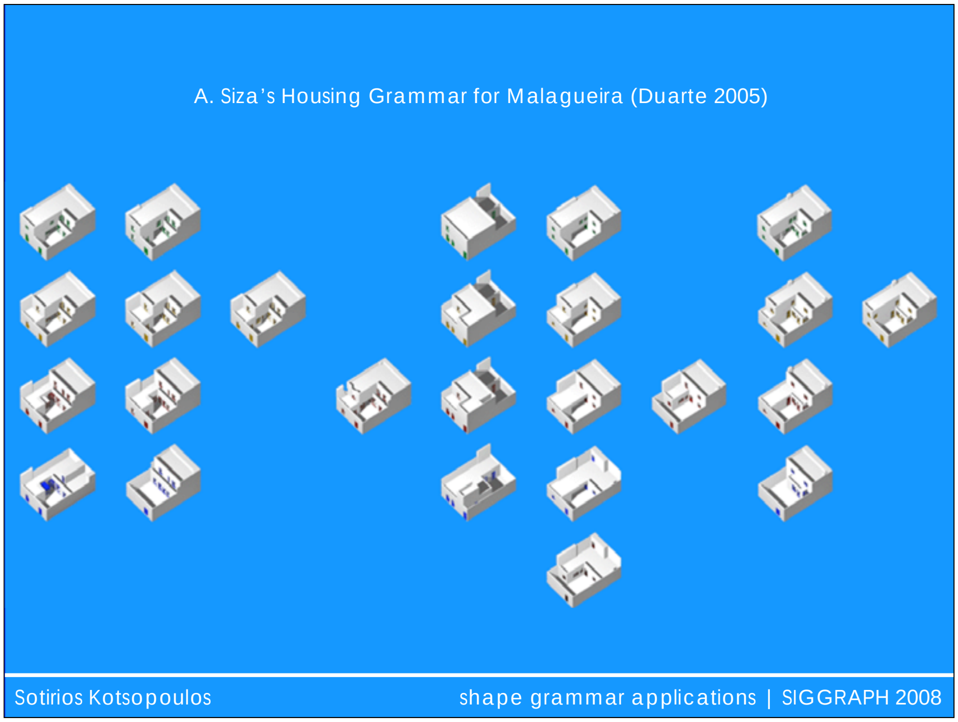
A fragment from a derivation that shows the consecutive subdivisions



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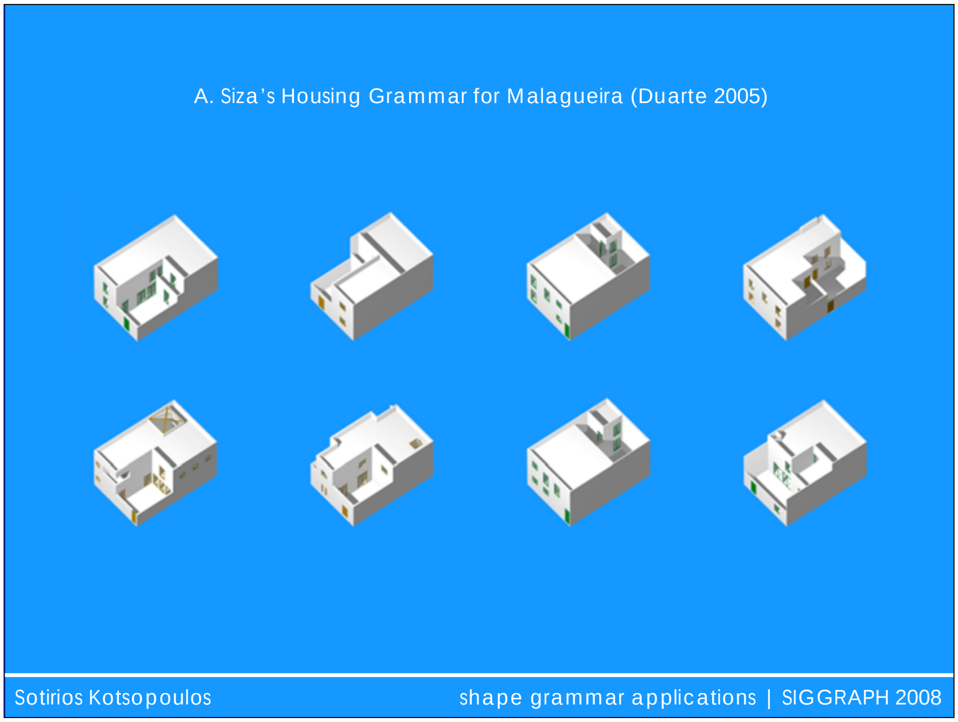
Designs produced by the Malagueira grammar that belong to the original language of Siza's designs.



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New designs generated by the same rules.

Habitat For Humanity Housing Grammar (Kotsopoulos 2005)

an elementary exercise in formal composition



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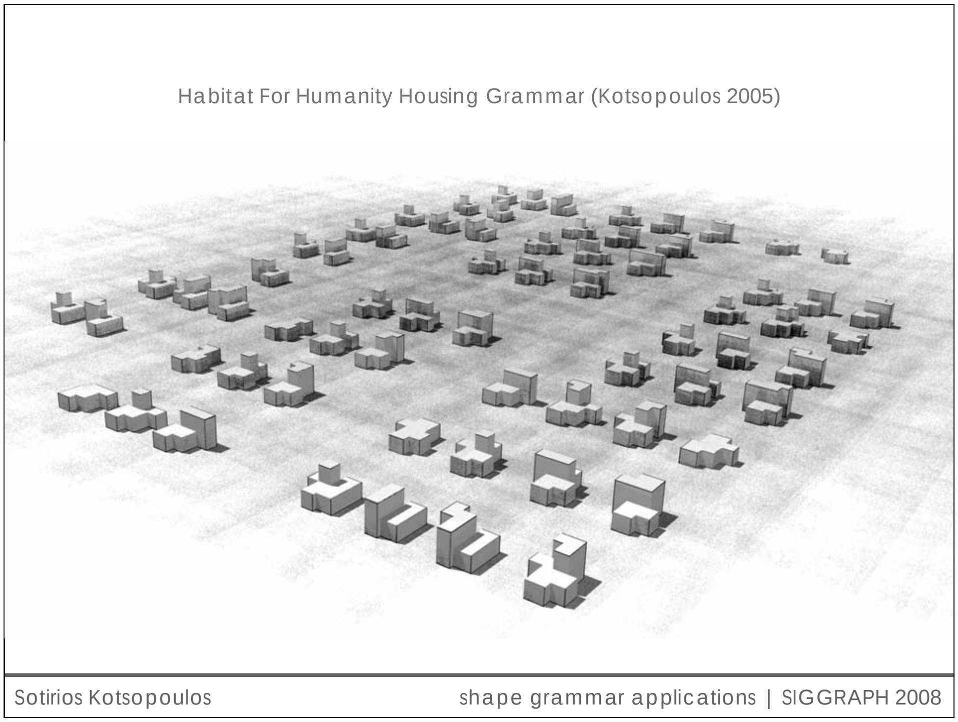
The example presents the generation of low cost housing units for Habitat For Humanity, from scratch. The building programs, the sites provided by HFH, and the examples of existing housing units, in Roxbury, Massachusetts, became a basis for the development of what was envisioned to be used as: “an elementary studio exercise in formal composition”.



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The housing units were approached as configurations of building blocks, or rooms. These configurations are produced by applying rules that are able to generate preferred adjacencies.

Habitat For Humanity Housing Grammar (Kotsopoulos 2005)

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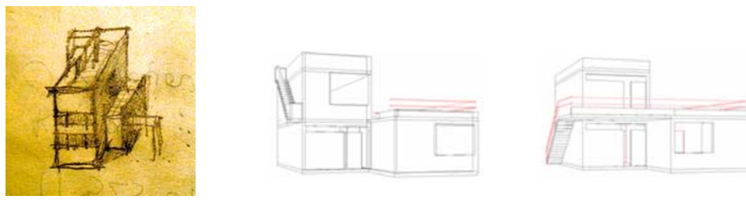
The rules are organized in different levels. General rules are used first to organize parties. At a different level, rules apply on selected parties to generate wall layouts, or to introduce openings. Some examples of the produced arrangements are presented above.

Habitat For Humanity Housing Grammar (Kotsopoulos 2005)



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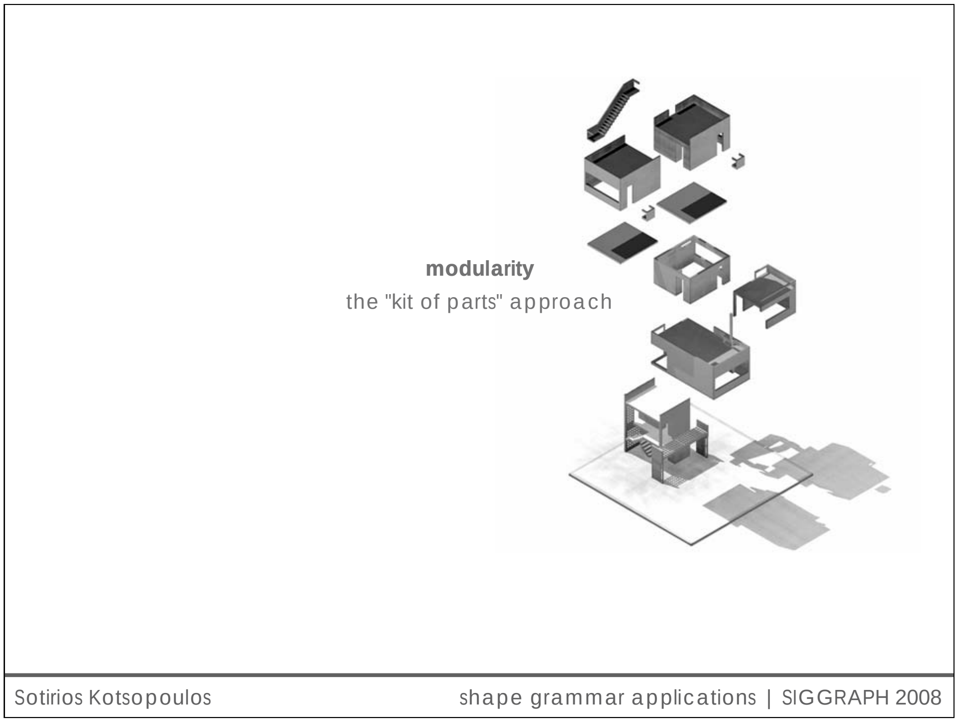
The process started naturally, from sketching possible houses (left). Digital models (right) were introduced at a later stage of this process.



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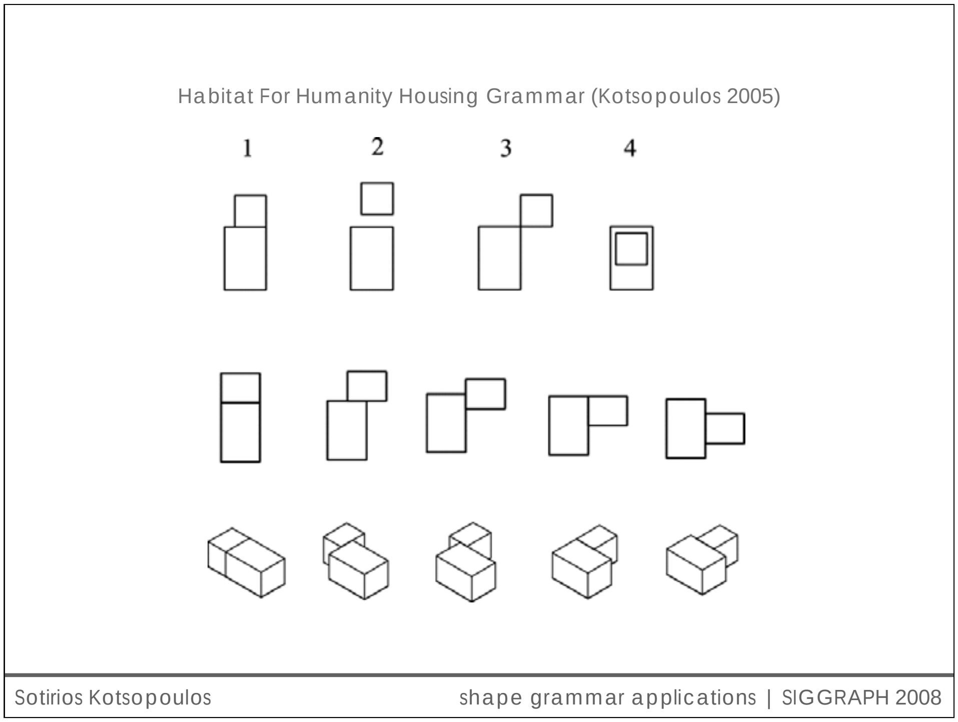
Key issue of the process was the gradual specification of a possible “kit of parts”. These combine to produce variation.



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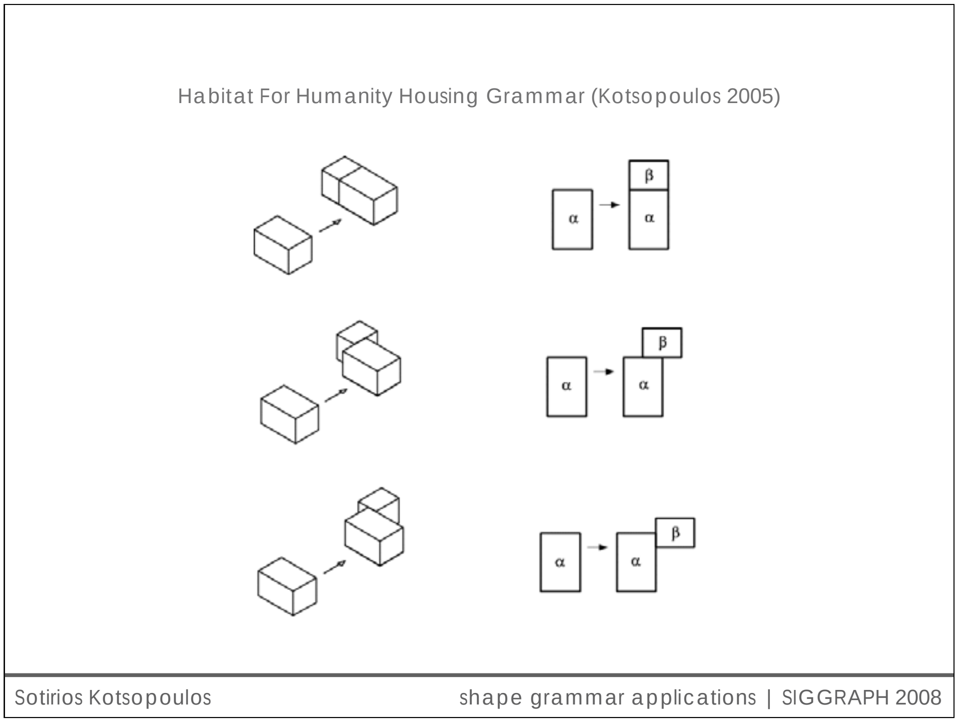
Four spatial relations between any two rooms are presented (first row): (1) having a common boundary, (2) being discrete, (3) touching in a corner, (4) overlapping. Five parametric variations (second row) of the first spatial relation are used in the proposed grammar.



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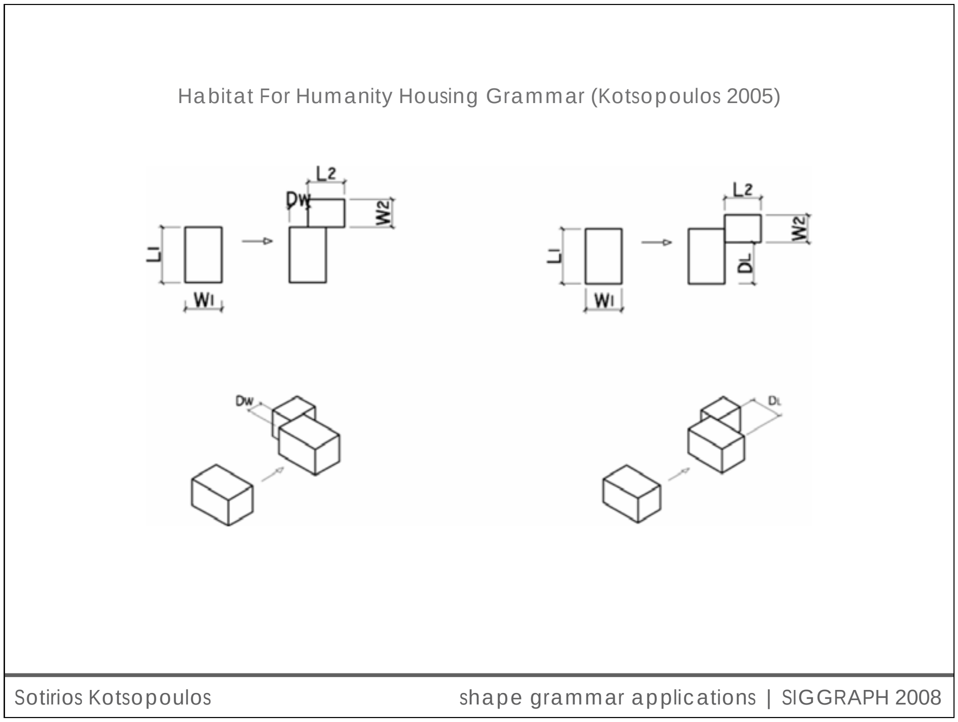
The spatial relations introduce corresponding parametric rules.



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The five parametric variations of spatial relations can be generated by the above two parametric rules.

shape grammar interpreter (Liew 2004)

converted the shape rules to machine instructions
to be executed by a digital machine

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A digital shape grammar interpreter was used to facilitate to express the rules in code and to automate the generation combinations rules described in LISP scripting language format

a rule is composed of four parts:

1. Left-hand schema
2. Right-hand schema
3. Transformation mapping
4. Parameter mapping

the geometry is described as a series of vectors. Each vector has three components:

1. Action
2. Vector
3. Label

a horizontal *parti* line that is 5 units long is described as:

```
((action "line") (vector 5 0) (label "parti"))
```


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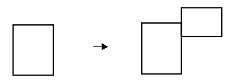
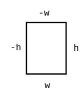
Lisp code was used to assist the fast generation of design alternatives. A line of length 5 is described as above.

an additive rule of the form x → x + y:



```
(setq schema-left-rule
  '((geometry
    ((action "line") (vector w 0) (label "parti"))
    ((action "line") (vector 0 h) (label "parti"))
    ((action "line") (vector (- w) 0) (label "parti"))
    ((action "line") (vector 0 (- h)) (label "parti"))
     )
    (parameter-constraints
       (w (> w 0))
       (h (> h w))
       )
     )
 )
```



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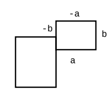
The above sequence of code expressions describe the left hand side of the rule.

```
(setq schema-right-rule
  ‘((geometry
    ((action "line") (vector w 0) (label "parti"))
    ((action "line") (vector 0 h) (label "parti"))
    ((action "line") (vector (- w) 0) (label
    "parti"))
    ((action "line") (vector 0 (- h)) (label
    "parti"))
    ((action "move") (vector w (- h (* 0.375 w))))
    ((action "line") (vector a 0) (label "parti"))
    ((action "line") (vector 0 b) (label "parti"))
    ((action "line") (vector (- a) 0) (label
    "parti“))    ((action "line") (vector 0 (- b))
    (label "parti"))
    )
  (parameter-constraints
    (w (> w 0))
    (h (> h w))
    (a (> a 0))
    (b (> b 0))
    )
   )
)
```



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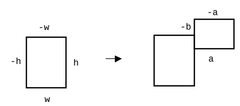
The above sequence of code expressions describe the right hand side of the rule

```
(setq tmap-rule
  '((delta-xo . 0)
    (delta-yo . 0)
    (delta-ro . 0)
    (delta-za . 0)
   )
)

(setq pmap-rule
  '((w . w)
    (h . h)
    (a . w)
    (b . (* 0.75 w))
   )
)

(setq housing-rule
  '((left . schema-left-rule)
    (right . schema-right-rule)
    (tmap . tmap-rule)
    (pmap . pmap-rule)
    (success . nil)
    (failure . nil)
    (applymode . "single")
    (rulename . "housing-rule")
   )
)
```



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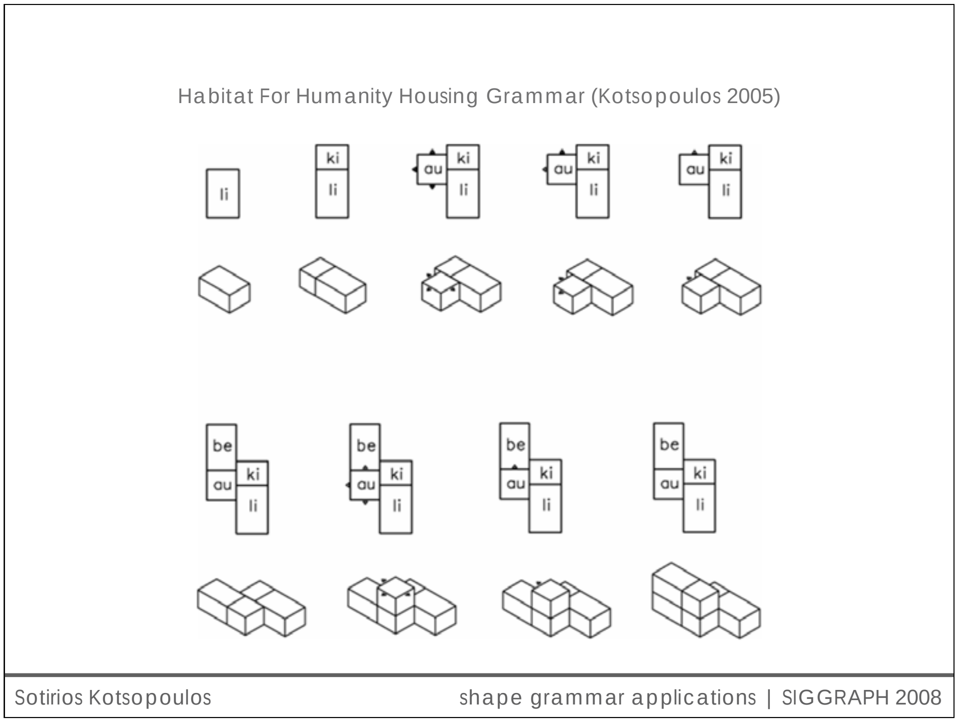
And, this final sequence of code expressions coordinate the left and right hand side of the rule, in rule application.



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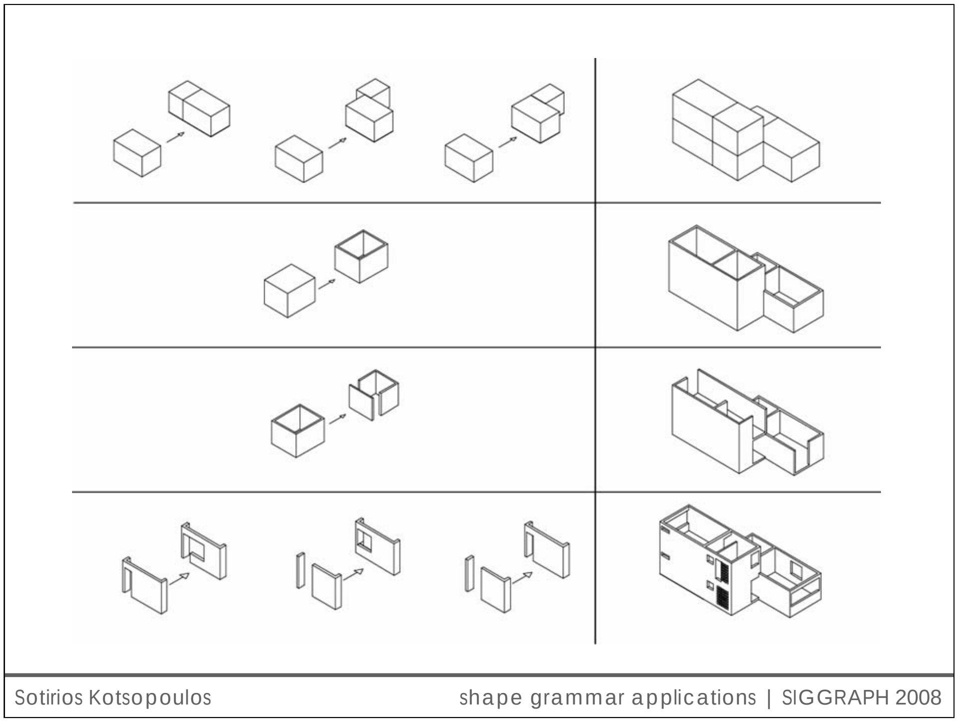
A possible derivation of a housing unit on the basis of the proposed rules



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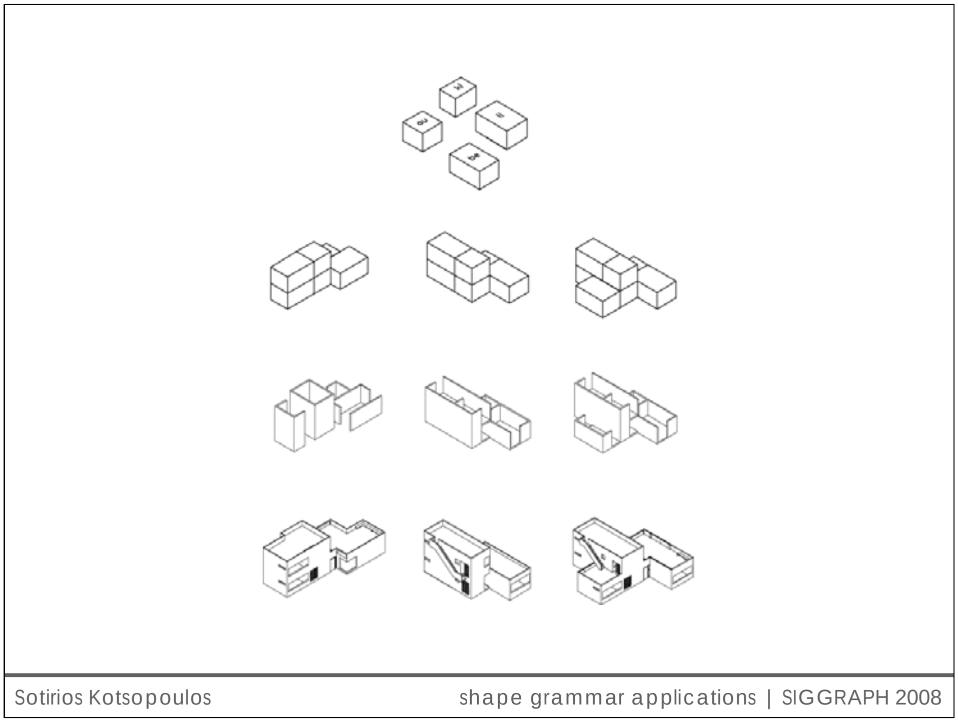
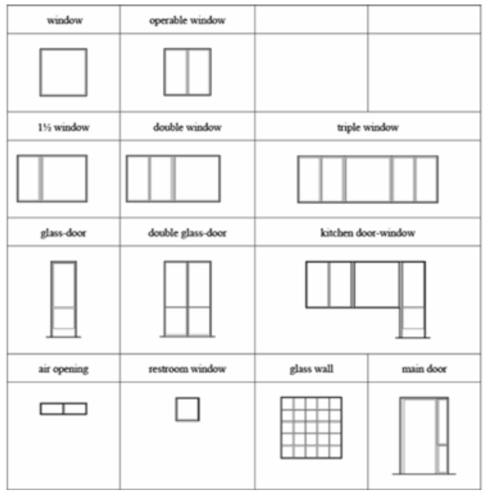
Different levels of rule-articulation: at he first row the rules produce diagrammatic parties. At the second row wall layouts, at he third row openings and at the fourth row windows and passages.



Slide 88

Different levels of rule-articulation: at he first row the rules produce diagrammatic parties. At the second row wall layouts, at he third row openings and at the fourth row windows and passages.



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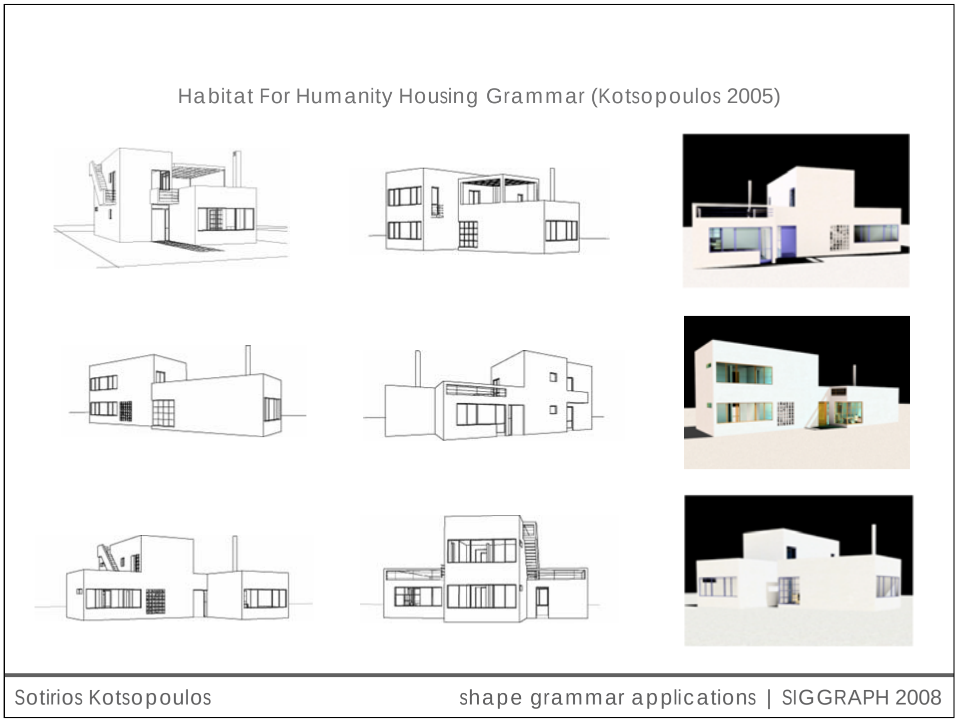
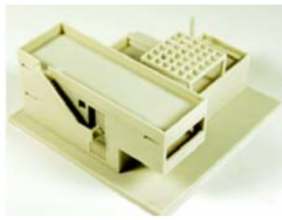
The vocabulary of doors and windows used in the exercise.

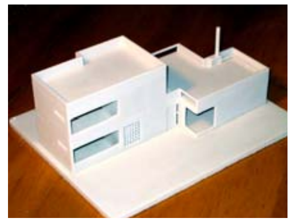


Slide 90

Some 3D modeled and rendered examples of housing units.

Habitat For Humanity Housing Grammar (Kotsopoulos 2005)





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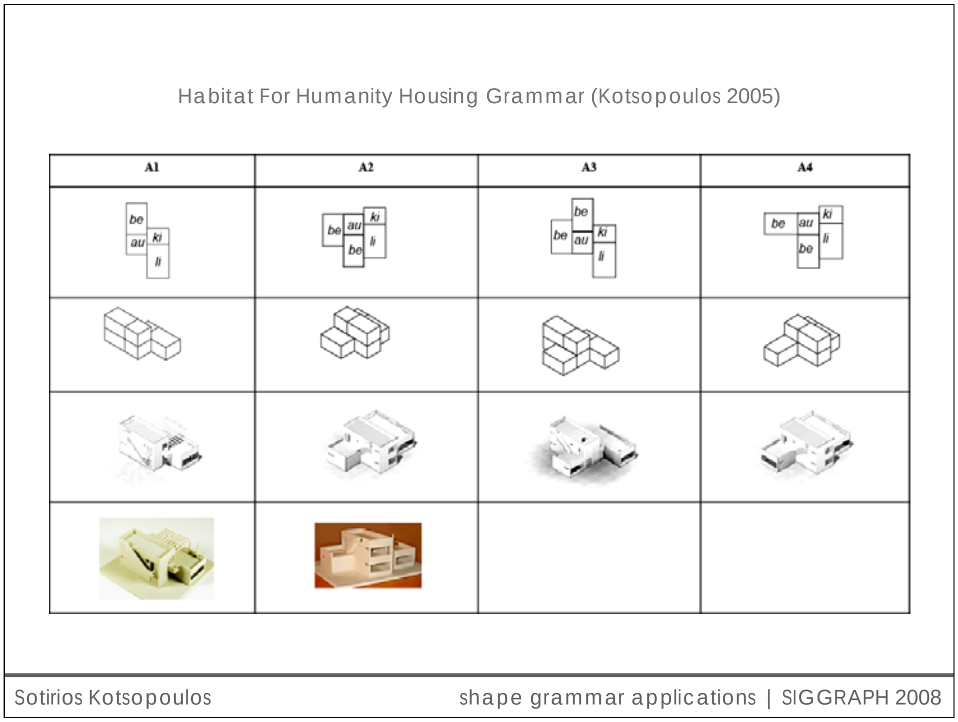
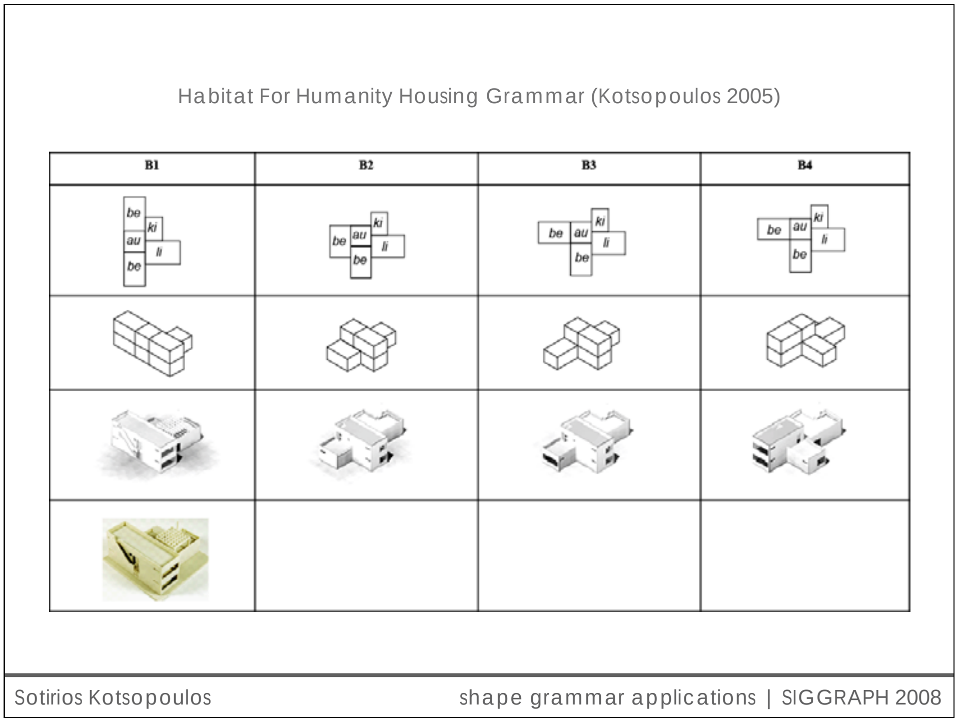
Slide 91

Some 3D printed examples of possible housing units.



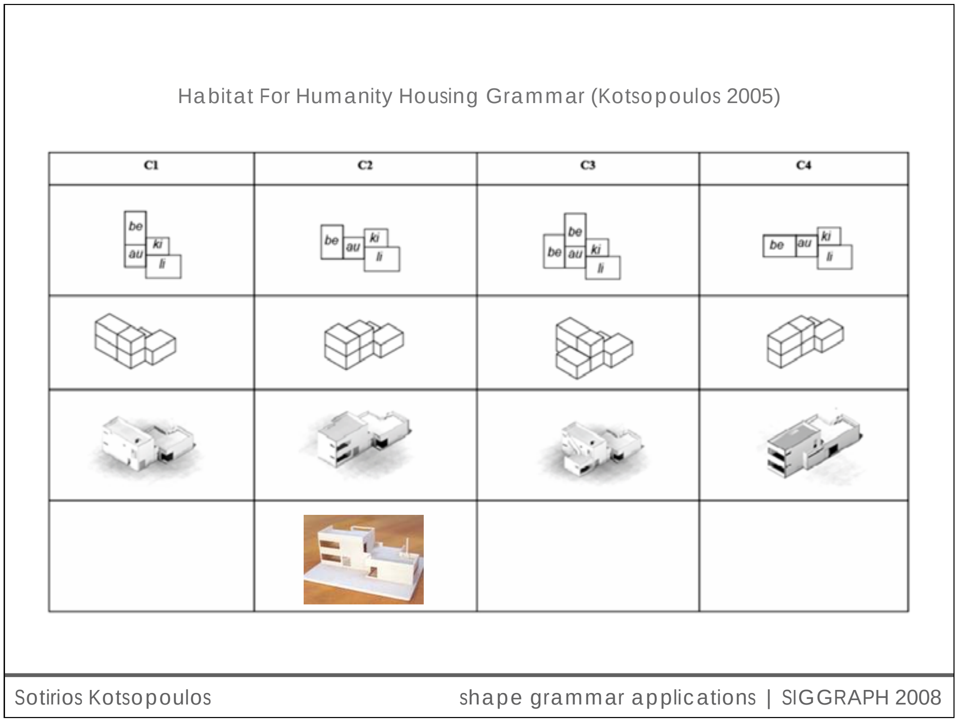
Slide 92

The sublanguage A of designs contains housing units produced by a specific set of rules.



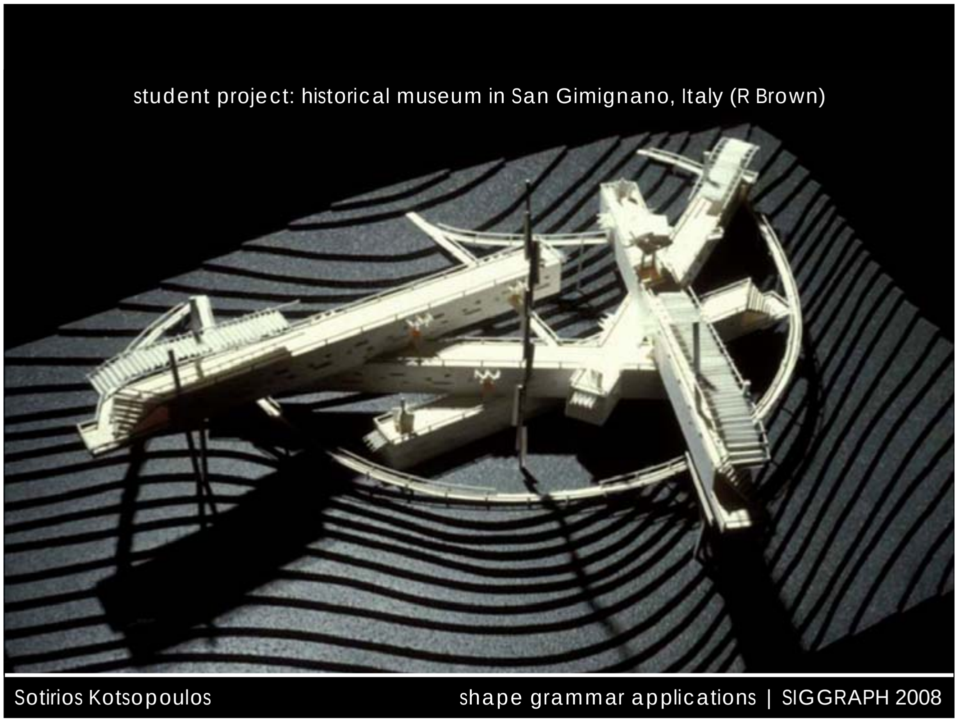
Slide 93

The sublanguage B, contains housing units produced by an alternative set of rules.



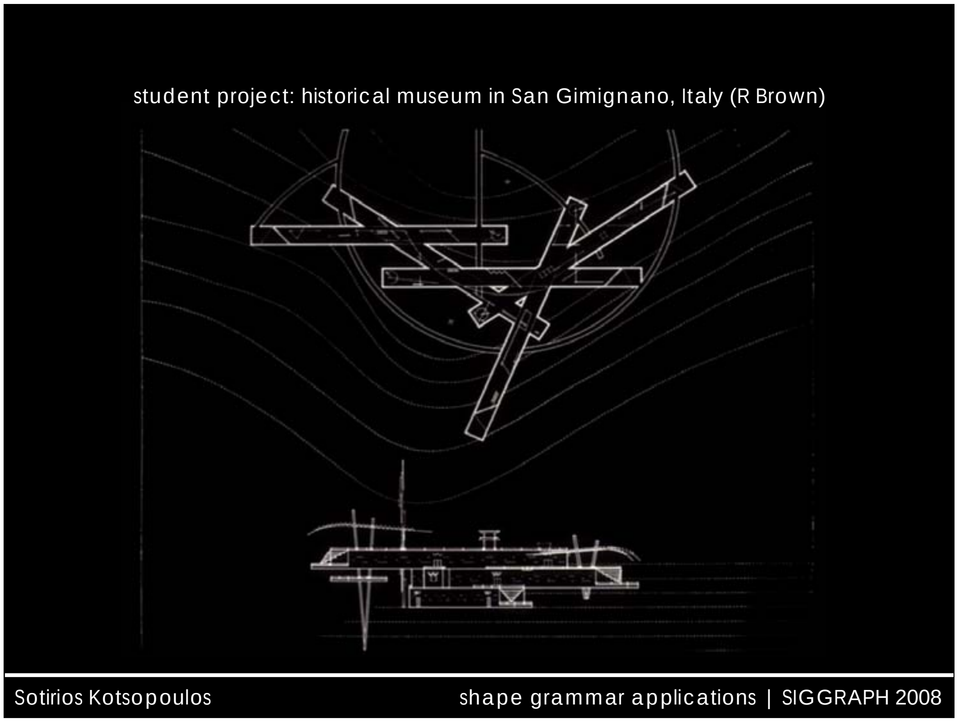
Slide 94

And, the sublanguage C contains housing units produced by a third alternative rule set.



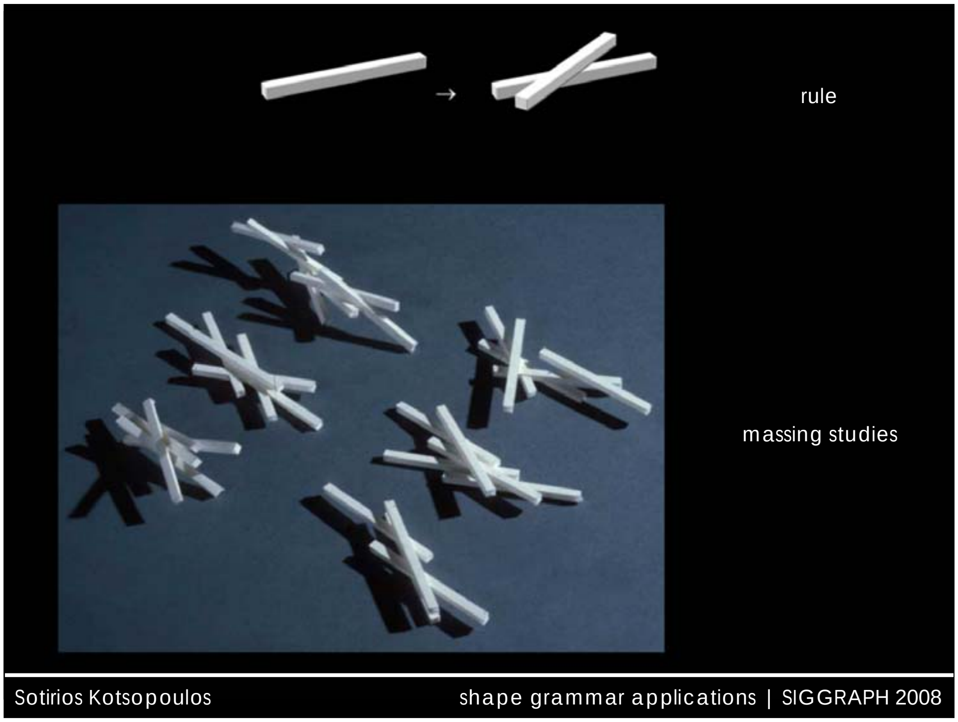
Slide 95

Another studio project using shape grammars in composition. The design for a historical museum in San Gimignano, Italy. Student R. Brown.



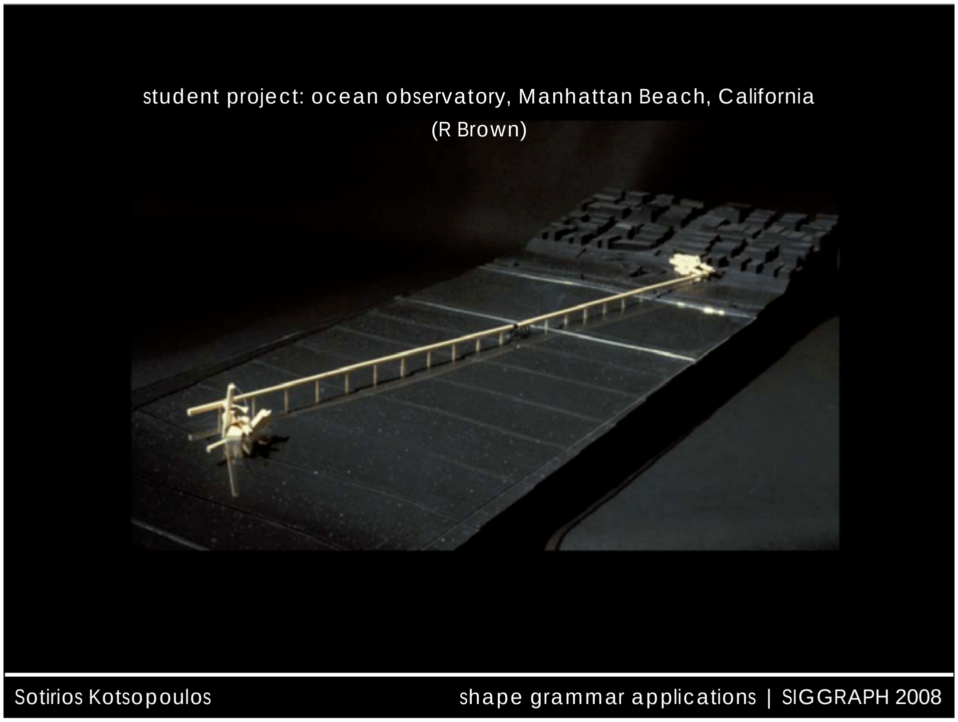
Slide 96

Plan arrangement (above) and elevation (below)



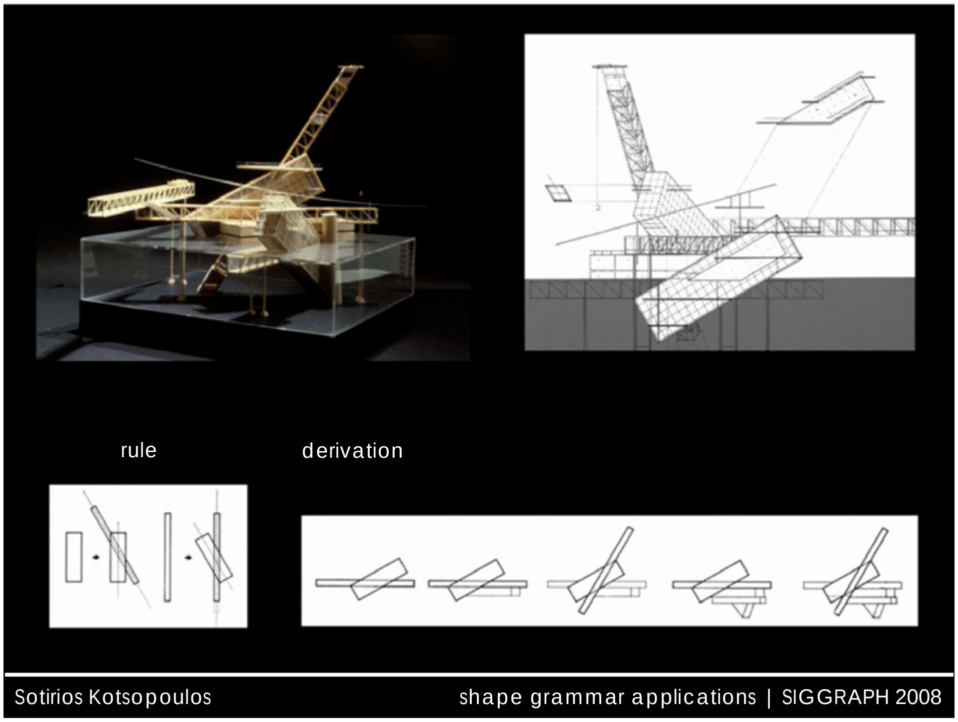
Slide 97

The underlying shape rule, presented above, guides the generation of several possible massing studies, for the building.



Slide 98

Studio project using shape grammars in composition. The design for an ocean observatory in Manhattan beach, CA. Student R. Brown.

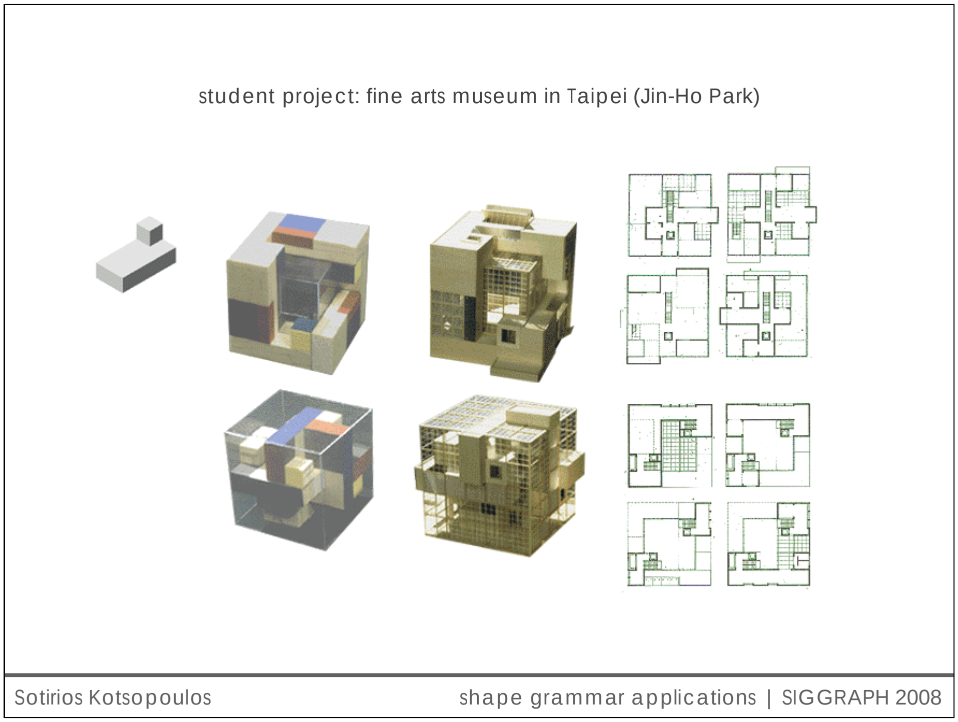


Slide 99

The underlying shape rule (bottom left), guides the generation of the building.

Slide 100

Studio project using shape grammars in composition. The design for a fine arts museum in Taipei. Student Jin-Ho Park.

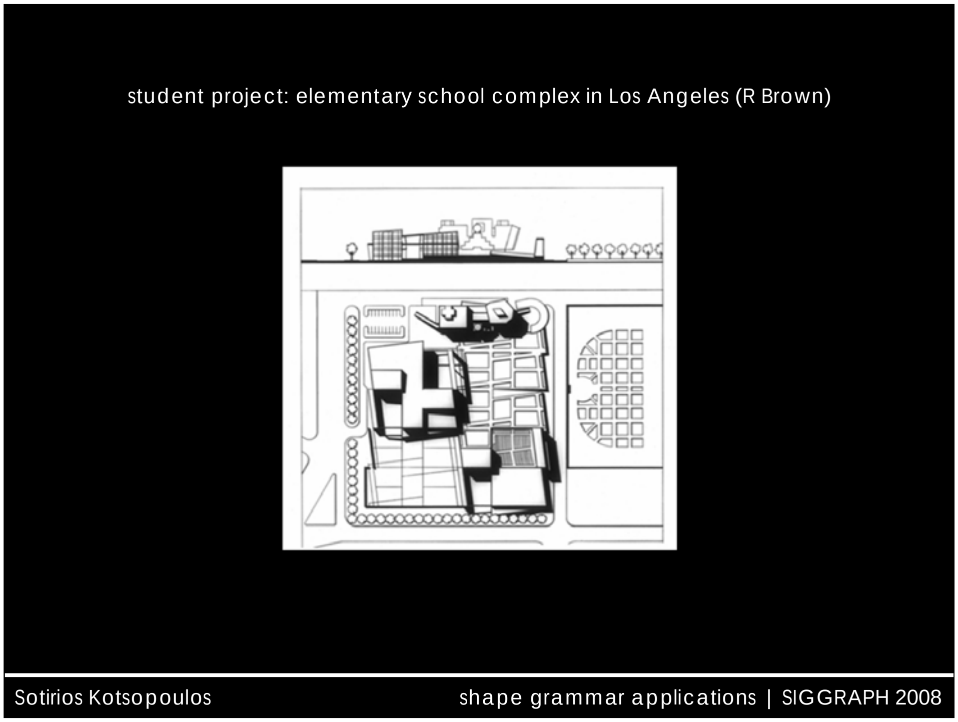


Slide 101

The composition begins with the definition of a spatial relationship between the participating shapes (left). Two schematic compositions are produced by applying the rule. Student Jin-Ho Park.

Slide 102

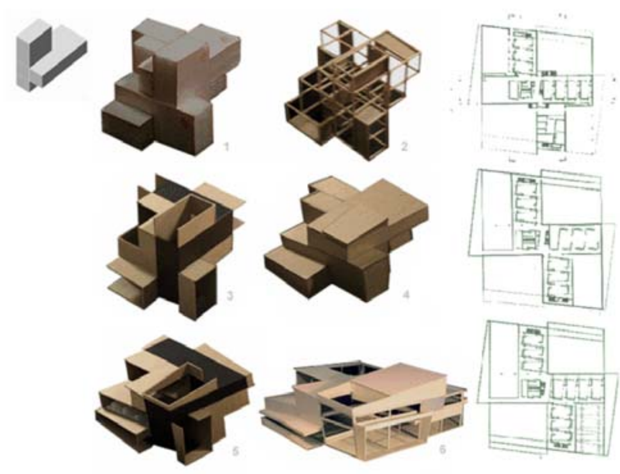
Studio project using shape grammars in composition. The design for an elementary school complex in Los Angeles. Student R Brown.



Slide 103

Overview of the proposed arrangement that was generated with rules and grammars.

student project: elementary school complex in Los Angeles (R Brown)



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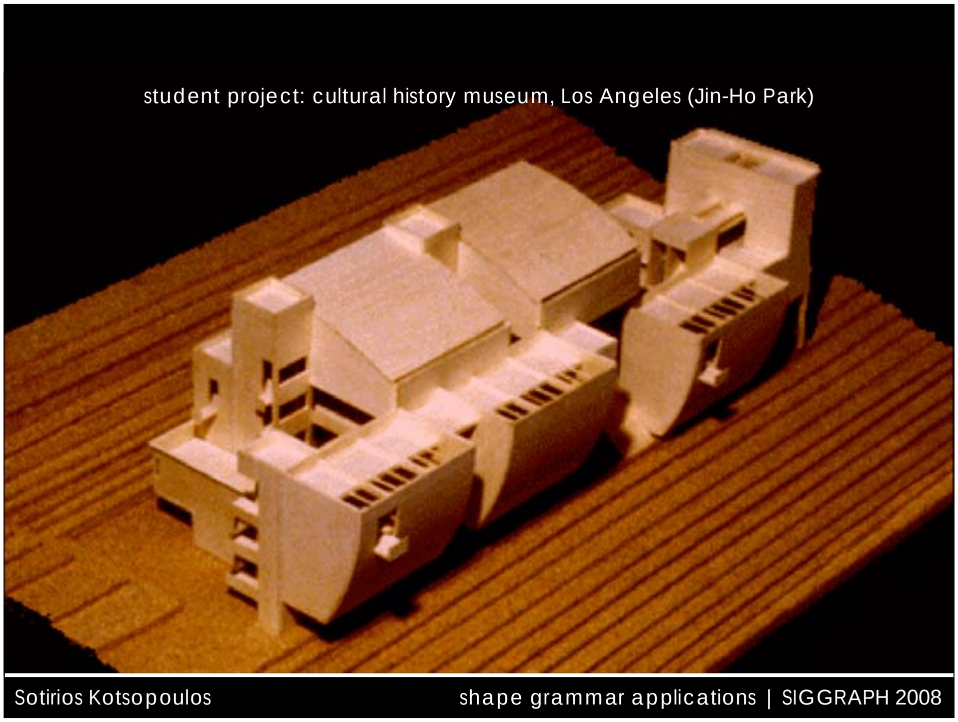
Slide 104

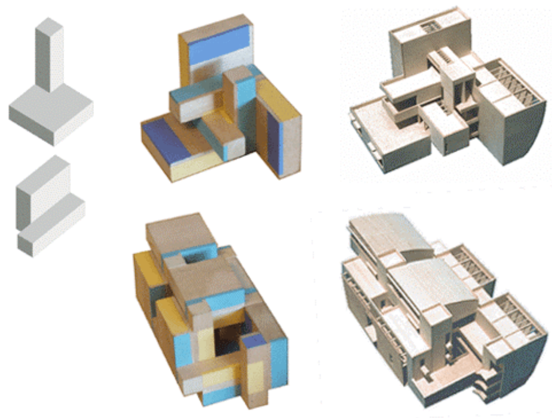
The composition starts with the definition of a spatial relationship between the participating forms (left). Three schematic compositions are produced by applying the rule. Student R, Brown.



Slide 105

Studio project using shape grammars in composition. The design for a cultural history museum in Los Angeles. Student Jin-Ho Park.

student project: cultural history museum, Los Angeles (Jin-Ho Park)



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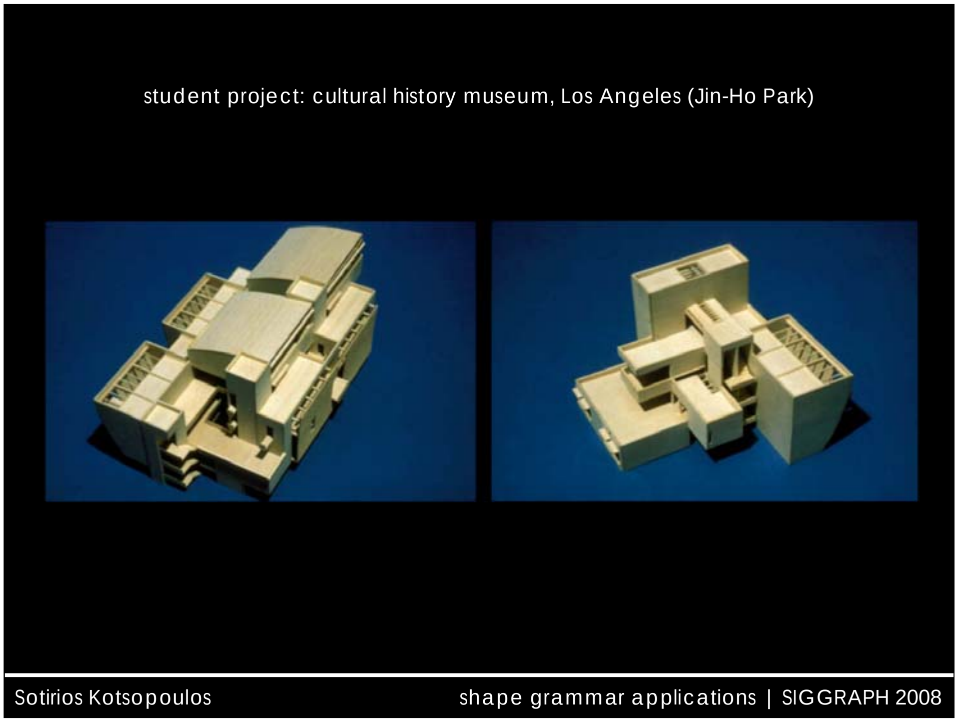
Slide 106

The generation of the composition is based on two spatial relationships between forms (left). Two schematic compositions are also presented above. Student R, Brown.

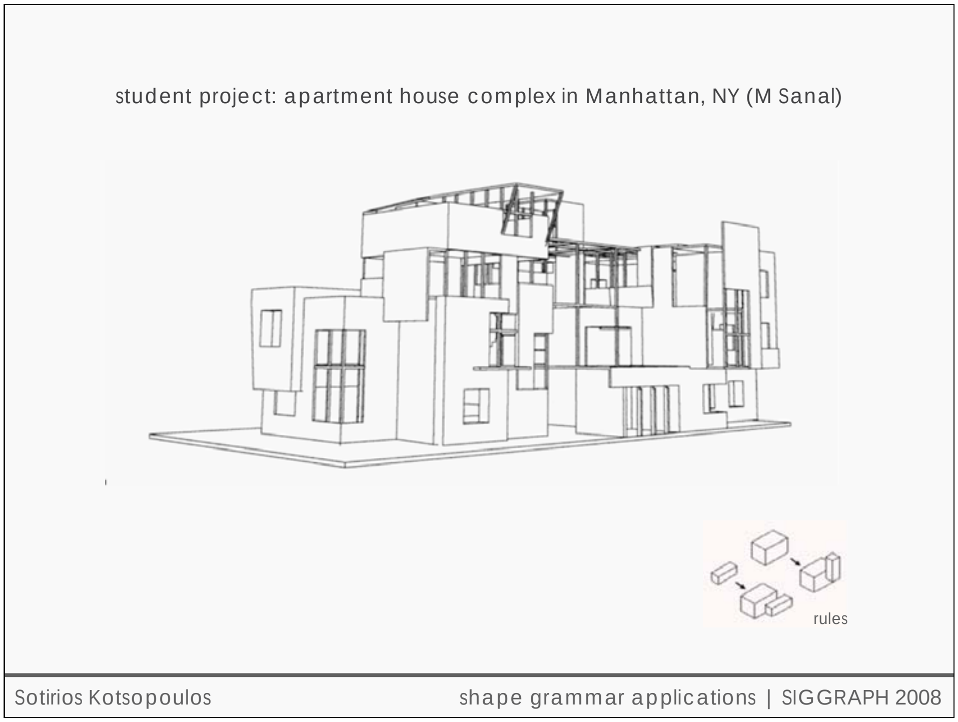


Slide 107

The design for a cultural history museum in Los Angeles. Student Jin-Ho Park.

Slide 108

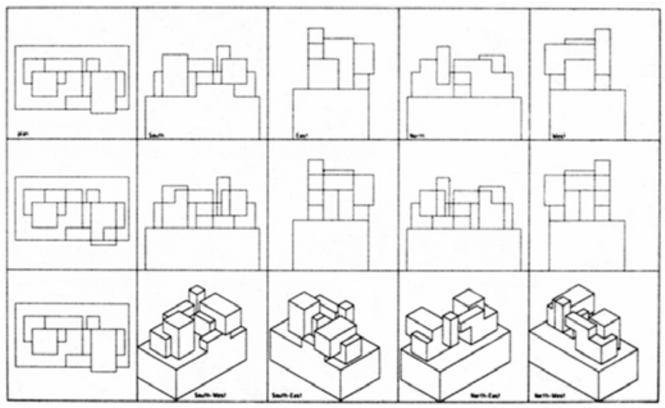
The designed building placed in the site. Student Jin-Ho Park.



Slide 109

Another example of use of shape grammars in composition. The design for an apartment house complex in Manhattan, NY. The two rules that are used to generate the design, appear at the right (bottom). Student M Sanal.

student project: apartment house complex in Manhattan, NY (M Sanal)



variations

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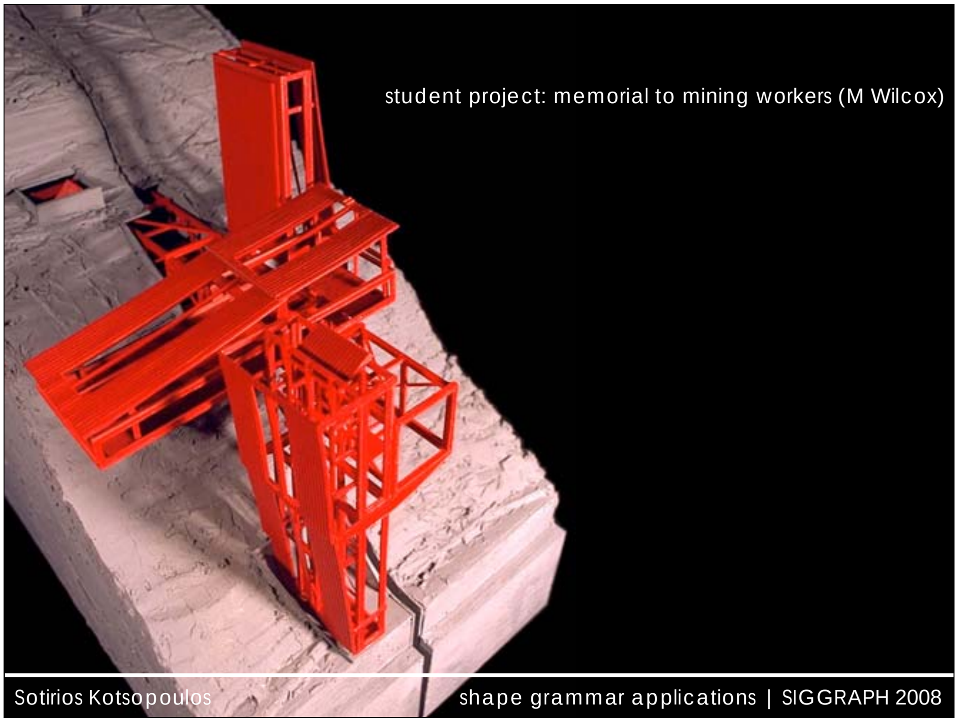
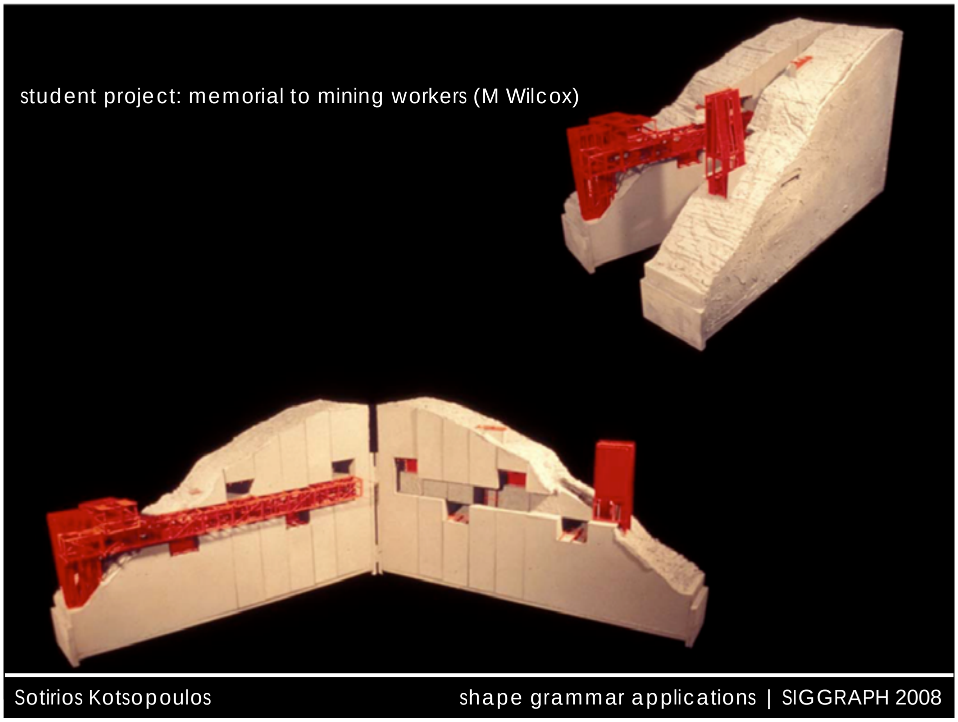
Slide 110

Design variations produced by the same two rules.



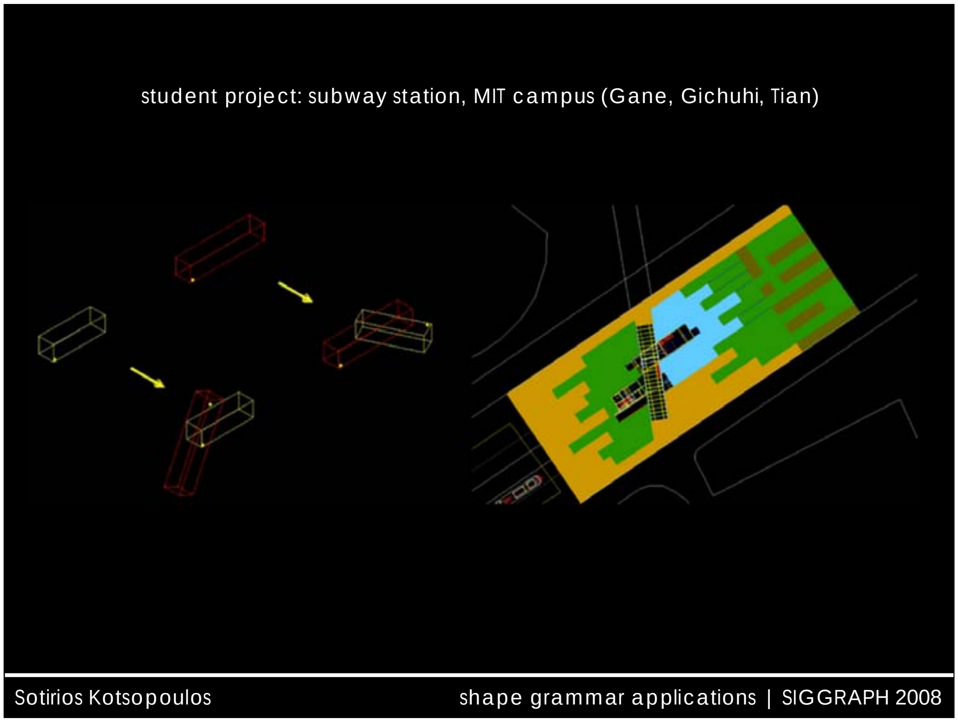
Slide 111

Example of the use of shape grammars in composition. A memorial to mining workers. Student M. Wilcox.



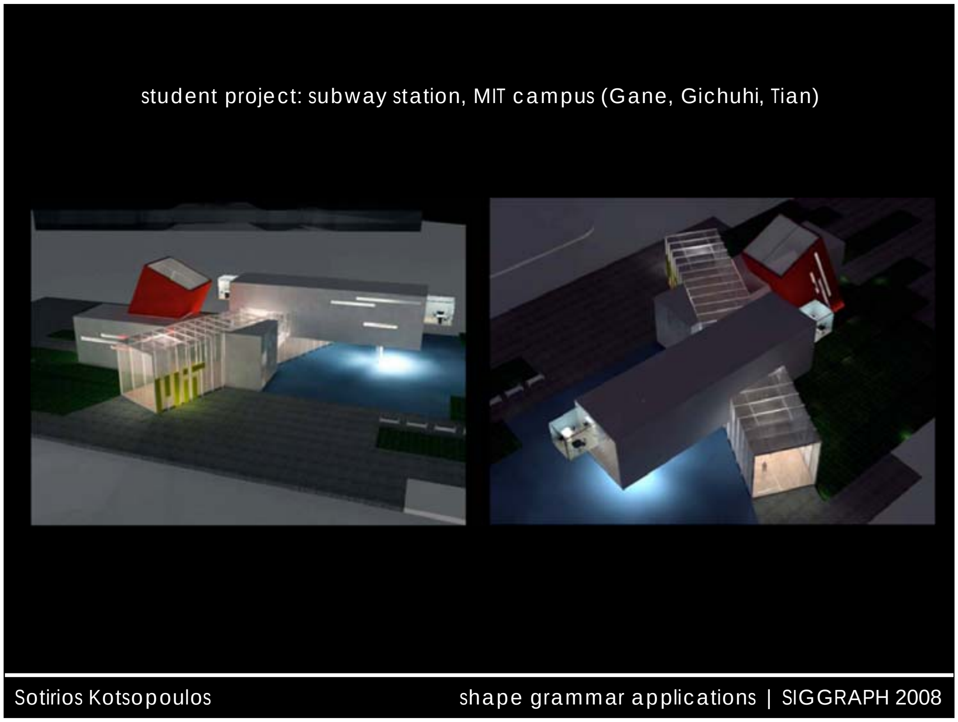
Slide 112

Large part of the proposed memorial remains underground



Slide 113

A more recent example of the use of shape grammars in composition. The design proposal for a subway station at MIT campus. The two rules on the left, and an overview of the produced arrangement on the right. Students: Gane, Gichuhi, Tian.



Slide 114

The design of the subway station in MIT campus, at night.

BIBLIOGRAPHY

Suggested reading

Stiny, George, 2006, *Shape,* MIT Press

References

Chomsky, N. 1957, *Syntactic Structures*, Mouton, The Hague

Duarte, J P, 2005, Towards the customization of mass-housing: the grammar of Siza's houses at Malagueira, *Environment and Planning B: Planning and Design*, 32, pp. 347-380

Flemming, U, 1987a, More than the sum of parts: the grammar of Queen Anne houses, *Environment and Planning B:Planning and Design 14* pp. 323-350

Flemming, U, 1990, Syntactic Structures in Architecture, The Electronic Design Studio, MIT Press, Cambridge pp. 31-47

Knight, T, 1980, The generation of Hepplewhite-style chair back designs, *Environment and Planning B: Planning andDesign 7* pp. 227-238

Knight, T, 1986, 'Transformation of the Meander Motif on Greek Geometric Pottery' *Design Computing 1* pp. 29-67

Knight, T, 1989, 'Transformations of De Stijl art: the paintings of Georges Vantongerloo and Fritz Glarner' *Environment and Planning B: Planning and Design 16* pp. 51-98

Koning H, and Eizenberg, J, 1981, The language of the prairie: Frank Lloyd Wright's prairie houses, *Environment andPlanning B: Planning and Design 8* pp. 295-323

Kotsopoulos, S D, Constructing Design Concepts: A computational approach to the synthesis of architectural form, Doctorate Dissertation, Massachusetts Institute of Technology.

Sass, L, 2007, A Palladian construction grammar-design reasoning with shape grammars and rapid prototyping *Environment and Planning B: Planning and Design 34* pp. 87-106

Stiny, G, 1977, Ice-ray: a note on Chinese lattice designs, *Environment and Planning B4* pp. 89-98

Stiny, G, 1980, Kindergarten grammars: designing with Froebel's building gifts, *Environment and Planning B 3*, pp. 409-462

Stiny, G 2006, *Shape,* MIT Press

Stiny, G and Gips, J, 1972, Shape Grammars and the Generative Specification, Petrocelli OR (ed) *Best computer papers of 1971*, pp. 125-135

Stiny, G and Mitchell, W J, 1978, The Palladian grammar, *Environment and Planning B 5* pp. 5-18

Ilustration Credits for Slides

Except for the two excerpts from Stiny and Gips (1972), all illustrations in Part I, including the remake of the nine step computation by Stiny (2006), are drawn by Mine Ozkar.

All images indicated as ‘student projects’ in Part II demonstrate student work from the course *Introduction to Shape Grammars I&II: Theory & Applications*, taught by Prof. T Knight since 1992 at UCLA and then MIT.

The presentation of the analysis on Simmons Hall dormitory contains sketches, photographs and models by Steven Holl Architects NY, as well as computer generated drawings and models by Sotirios Kotsopoulos.