SHAPE GRAMMARS AND THE GENERATIVE SPECIFICATION OF PAINTING AND SCULPTURE

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Abstract

A method of shape generation using shape grammars which take shape as primitive and have shape-specific rules is presented. A formalism for the complete, generative specification of a class of non-representational, geometric paintings or sculptures is defined which has shape grammars as its structural component. Paintings are material representations of two-dimensional shapes generated by shape grammars, sculptures of three-dimensional shapes. Implications for aesthetics and design theory in the visual arts are discussed. Aesthetics is considered in terms of specificational simplicity and visual complexity. In design based on generative specifications, the artist chooses structural and material relationships and then determines algorithmically the resulting works of art.

SHAPE GRAMMARS AND THE GENERATIVE SPECIFICATION OF PAINTING AND SCULPTURE

In this paper we present (1) a definition of shape grammars, (2) a formalism, based on these grammars, for the complete, generative specification of a class of paintings or sculptures, and (3) a discussion of the implications of these specifications for aesthetics and design theory. Generative specifications can be used in the analysis and aesthetic evaluation of the paintings or sculptures they define. In design based on generative specifications, the artist chooses structural and material relationships and then produces algorithmically the resulting works of art. Our underlying aim is to use formal, generative techniques to produce good works of art and to develop understanding of what makes good works of art.

The class of paintings shown in Figure 1 is used as an explanatory example. Additional paintings and sculptures defined by generative specifications are shown in the Appendix.

1 Background

The shape formalism defined is in the tradition of that research in pattern recognition which has been structurally or syntactically oriented. Formal syntactic systems were first introduced by Chomsky in linguistics as phrase structure grammars (Chomsky, 1957). Eden (1961) and Narasimhan (1962) were

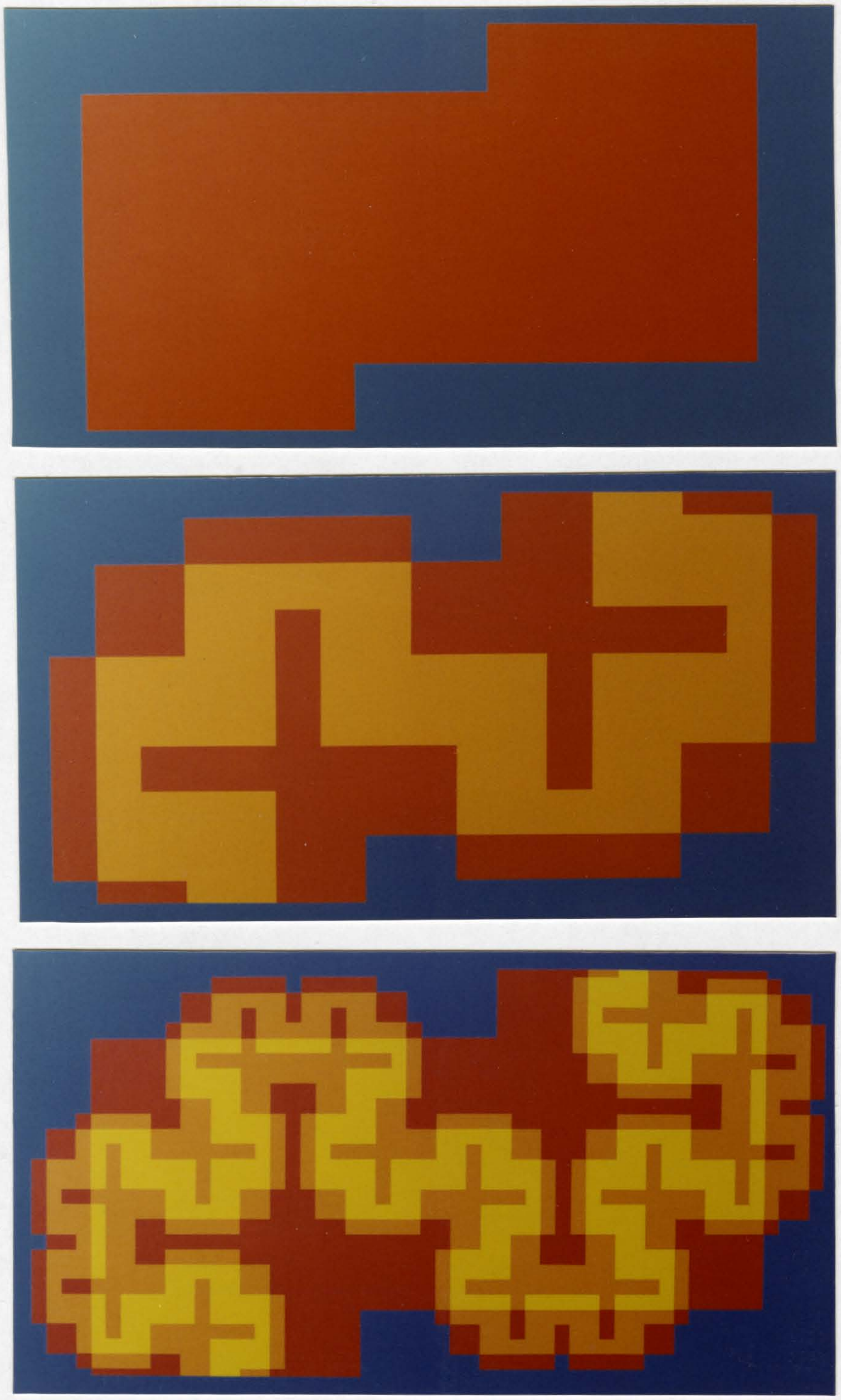


Figure 1
Urform I, II, and III
(Stiny, 1970. Acrylic on canvas, each canvas 30 ins. X 57 ins.)

the first to propose and demonstrate the use and value of syntactic techniques in pattern recognition. Miller and Shaw (1968) have surveyed results in this field. Important recent work includes (Evans, 1969) and (Shaw, 1969). The emphasis of most of this work has been on pattern analysis in terms of pattern grammars which are property specific. The emphasis in this paper is on pattern (shape) generation in terms of pattern (shape) grammars which are pattern (shape) specific.

The painting and sculpture we exhibit is in the tradition of non-representational, geometric art. Formal or mathematical approaches to art can be traced as far back as the ancient Greeks, *e.g.* Pythagoras and Polykleitos. Various modern artists and critics have stressed the use and applicability of formal systems in the visual arts. Focillon (1948) outlines the properties of a general morphology or syntax of forms for artistic design and analysis. Recent discussions of the use of systems in non-representational, geometric art can be found in (Hill, 1968). Typically these systems are inexplicit and at the level of mathematical sophistication of arithmetic and geometric progressions. They provide merely a structural motif presented in a painting or sculpture instead of a complete and effective specification for the generation of a painting or sculpture.

2 Shape Grammars

The definition of shape grammars given is one of several possible definitions which take shape as primitive and have rules which are shape specific. This definition was selected because it was found to be the most suitable as the structural component of our painting and sculpture formalisms.

2.1 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 $V_T^* \cap V_M = \emptyset$.
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 $u \longrightarrow v$. I is called the *initial shape* and normally contains a u such that there is a (u,v) which is an element of R. In shape grammars, shape is assumed to be primitive, *i.e.*, definitions are made ultimately in terms of shape.

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 occurence 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.

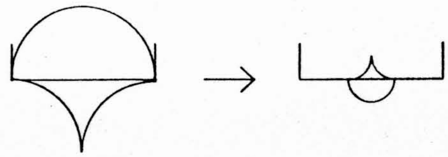
2.2 Example

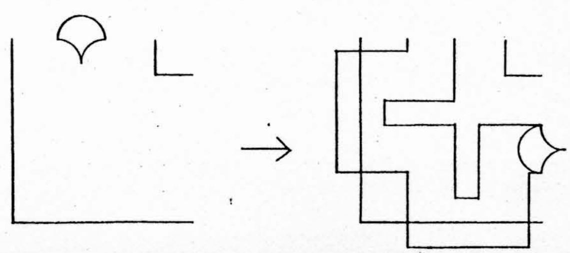
A shape grammar, SG1, is shown in Figure 2. V_T contains a straight line; terminals consist of finite arrangements of

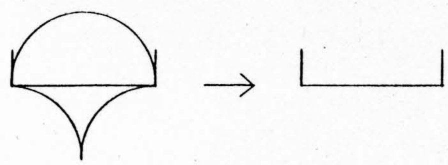
$SG1 = \langle V_T, V_M, R, I \rangle$

$V_T = \{ — \}$ $V_M = \{$  $\}$

R CONTAINS:

1. 

2. 

3. 

I IS:

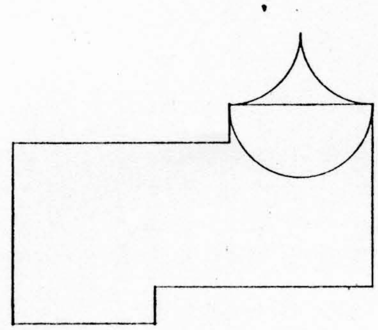


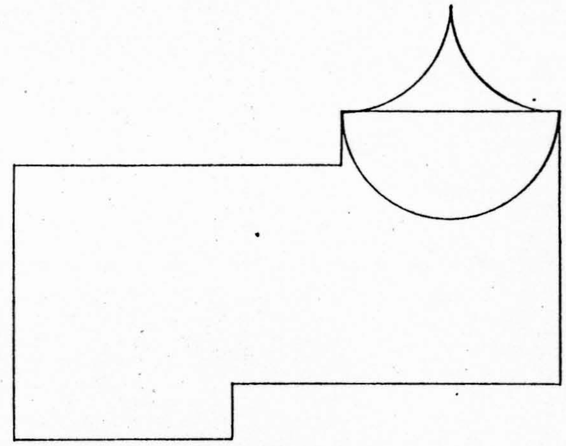
Figure 2
Shape grammar SG1

straight lines. V_M consists of a single element. R contains three rules——one of each type allowed by the definition. The initial shape contains one marker.

The generation of a shape in the language, L(SG1), defined by SG1 is shown in Figure 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 shapes indicated in steps 0, 3, and 18. Application of rule 3 results in the removal of the marker, the termination of the generation process (as no rules are now applicable), and a shape in L(SG1). Application of rule 1 reverses the direction of the marker, reduces it in size by one-third, and forces the continuation of the generation process. Markers restrict rule application to a specific part of the shape and indicate the relationship in scale between the rule applied and the shape to which it is applied. Rule 2 is the only rule applicable to the shape indicated in steps 1, 2, and 4–17. Application of rule 2 adds a terminal to the shape, advances the marker, and forces the continuation of the generation process. Shape generation using SG1 may be regarded in this way: the initial shape contains two connected "L"'s, and additional shapes are formed by the recursive placement of seven smaller "L"'s on each "L" such that all "L"'s of the same size are connected. Notice that the shape produced in this way can be expanded outward indefinitely but is contained within a finite area. The language defined by SG1 is shown in Figure 4.

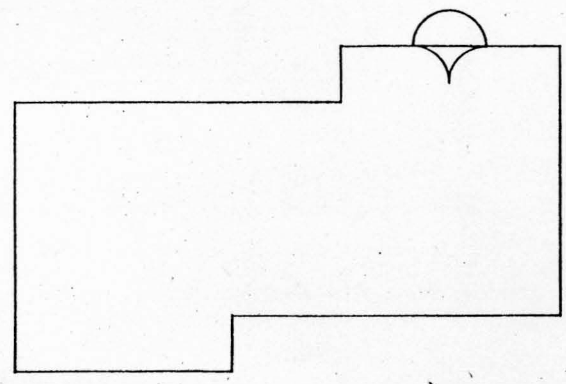
STEP RULE SHAPE

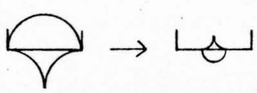
0.



(INITIAL SHAPE)

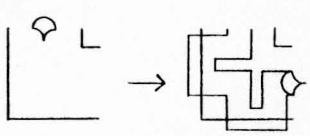
1.

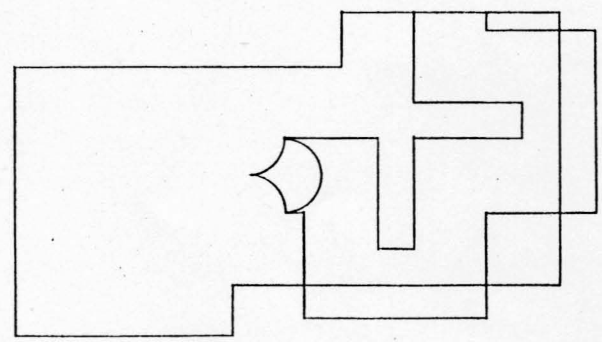




(RULE 1)

2.

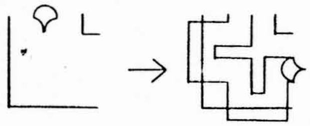




(RULE 2)

Figure 3, page 1

3.



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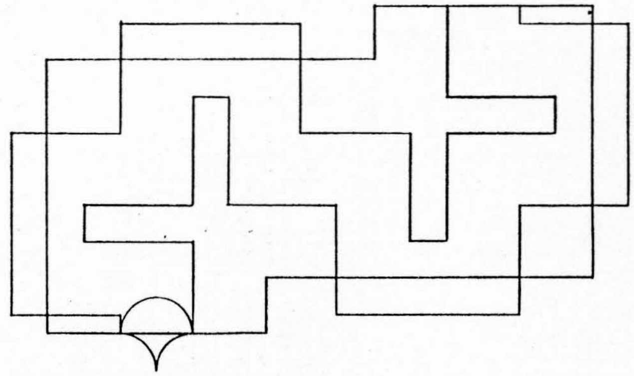
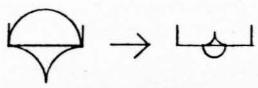
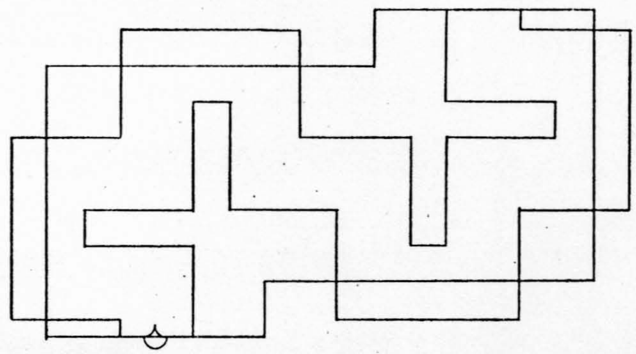


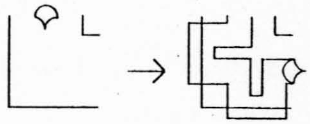
4.



(RULE 1)



5.



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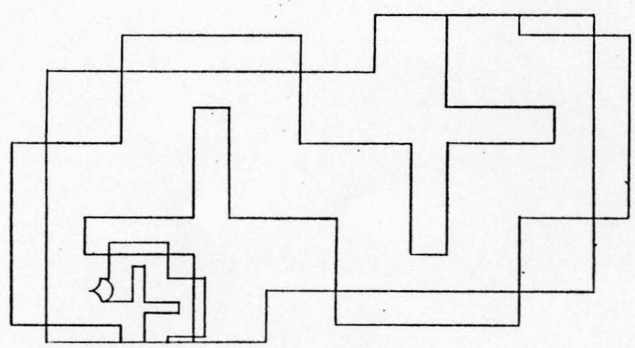

Figure 3, page 2

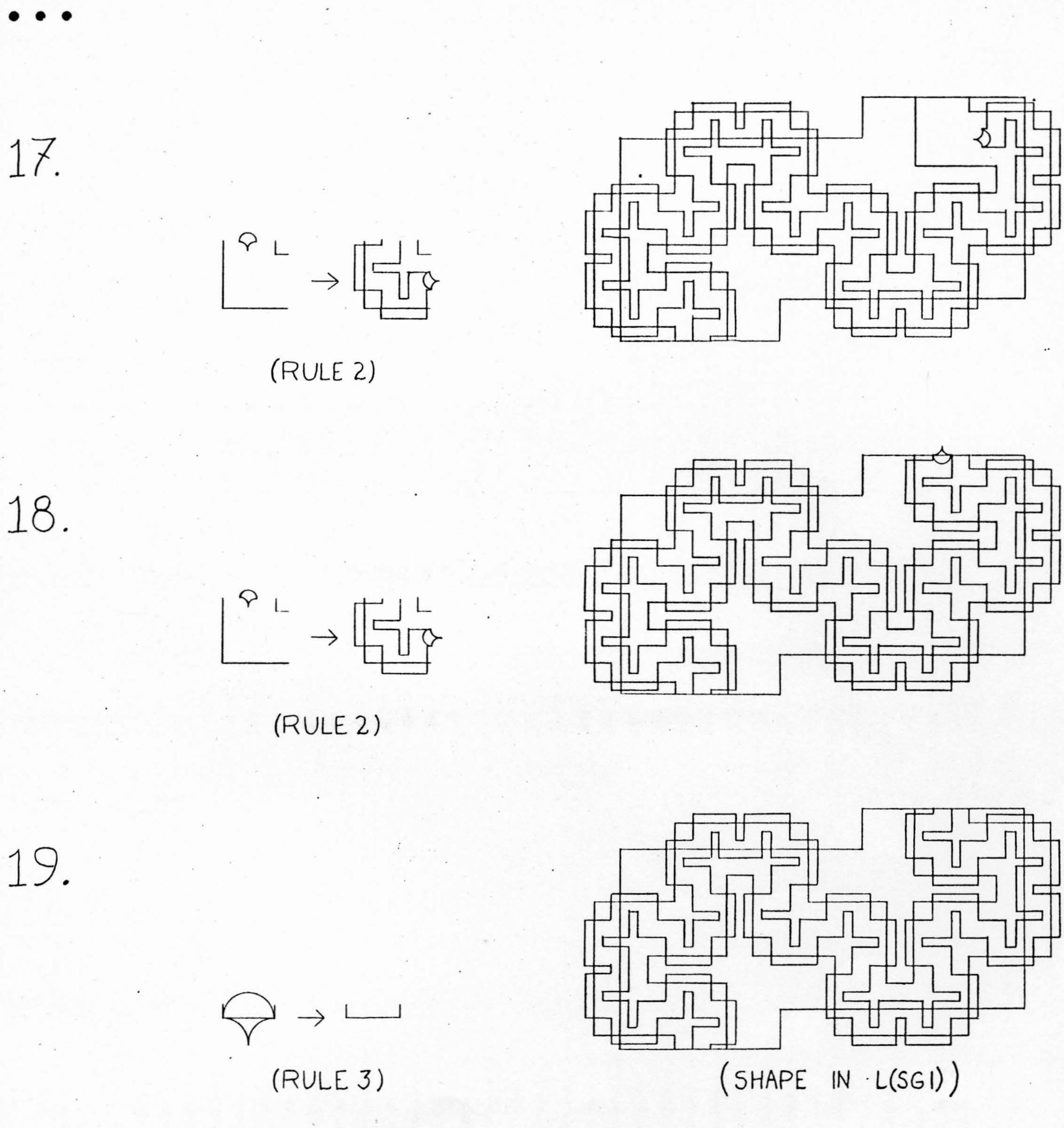

Figure 3, page 3
Generation of a shape using SG1

L(SG1) CONTAINS

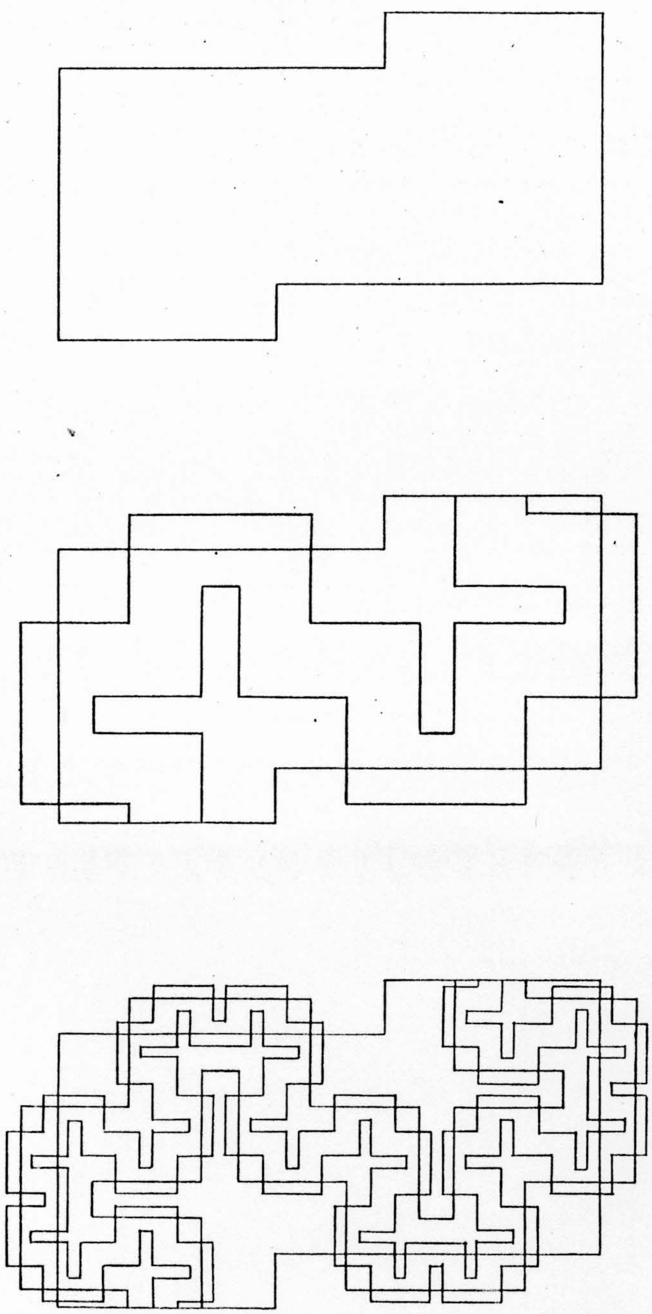

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Figure 4
The language defined by SG1, L(SG1)

2.3 N — Dimensional Languages

SG1 defines a language containing shapes of two dimensions. Grammars can be written to define languages containing shapes with dimension greater than two. As it is difficult to meaningfully represent the rules of these grammars on two-dimensional paper an example is not included in this section. Sculptures generated from grammars which define three-dimensional languages are shown in the Appendix.

2.4 Discussion

The definition of shape grammars allows rules of three types. Where rule type B is logically redundant in the system, it was included because it was found useful in defining painting and sculpture formalisms. Different rule types consistent with the idea of shape grammars are possible and can define classes of grammars analogous to the different classes of phrase structure grammars (Ginsberg, 1966).

Where we use shape grammars exclusively to generate shapes for painting and sculpture, they can be used to generate musical scores, flowcharts, structural descriptions of chemical compounds, the sentences——and their tree structures——in phrase structure languages, etc.

3 Painting and Sculpture

The painting and sculpture discussed are material representations of shapes generated by shape grammars. The complete, generative specification of these objects is made in terms of a structural component and a related material component. Each specification defines a finite class of related paintings or sculptures. Where a single painting or sculpture is to be considered uniquely, as is traditional, the class can be defined to contain only one element. Where several paintings or sculptures are to be considered serially or together to show the repeated use or expansion of a motif, as has become popular, the class can be defined to contain multiple elements. Discussion and illustrations of serial imagery in recent art can be found in (Coplans, 1968).

3.1 Painting

Informally, painting consists of the definition of a language of two-dimensional shapes, the selection of a shape in that language for 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.

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*) located with respect to the initial shape of the grammar with scale indicated.

3.1.1 Shape Specification

Shape grammars provide the basis for shape specification in painting. Painting requires a small class of shapes which are not beyond its techniques for representation. Because a shape grammar can define a language containing a potentially infinite number of shapes ranging from the simple to the very (infinitely) complex, a mechanism (selection rule) is required to select shapes in the language for paintings. The concept of *level* provides the basis for this mechanism and also for the painting rules discussed in the next section.

The level of a terminal in a shape is analogous to the depth of a constituent in a sentence defined by a context free phrase structure grammar. Level assignments are made to terminals during the generation of a shape using these rules:

1) The terminals in the initial shape are assigned level 0.
2) If a shape rule is applied, and the highest level assigned to any part of the terminal corresponding to the left side of the rule is N then
   a) if the rule is of type A, any part of the terminal enclosed by the marker in the left side of the rule is assigned N.
   b) if the rule is of type B, any part of the terminal enclosed by the marker in the left side of the rule is assigned N and any part of the terminal enclosed by the marker in the right side of the rule is assigned N + 1.

c) if the rule is of type C, the terminal added is assigned N + 1.

3) No other level assignments are made.

Parts of terminals may be assigned multiple levels. The marker must be a closed shape for rules 2a and 2b to apply. Rules 1 and 2c are central to level assignment; rules 2a and 2b are necessary for boundary conditions. The outlines of the three levels defined by level assignment in the example are shown individually in Figure 5.

A selection rule is a double (m,n), where m and n are integers. m is the minimum level required and n is the maximum level allowed in a shape generated by a shape grammar for it to be a member of the class defined by S. Because the terminals added to a shape during the generation process cannot be erased and level assignments are permanent, the selection rule may be used as a halting algorithm for shape generation. The class of shapes containing just the three shapes in Figure 4 is specified by the double (SG1,(0,2)). The minimum level required is 0 (all shapes in L(SG1) satisfy this requirement) and the maximum level allowed is 2 (only three shapes in L(SG1) satisfy this requirement).

3.1.2 Material Specification

The material specification of shapes in the class defined by S consists of two parts: painting rules and a limiting shape.

Painting rules define a schema for painting the areas contained in a shape. Level assignment provides a basis for

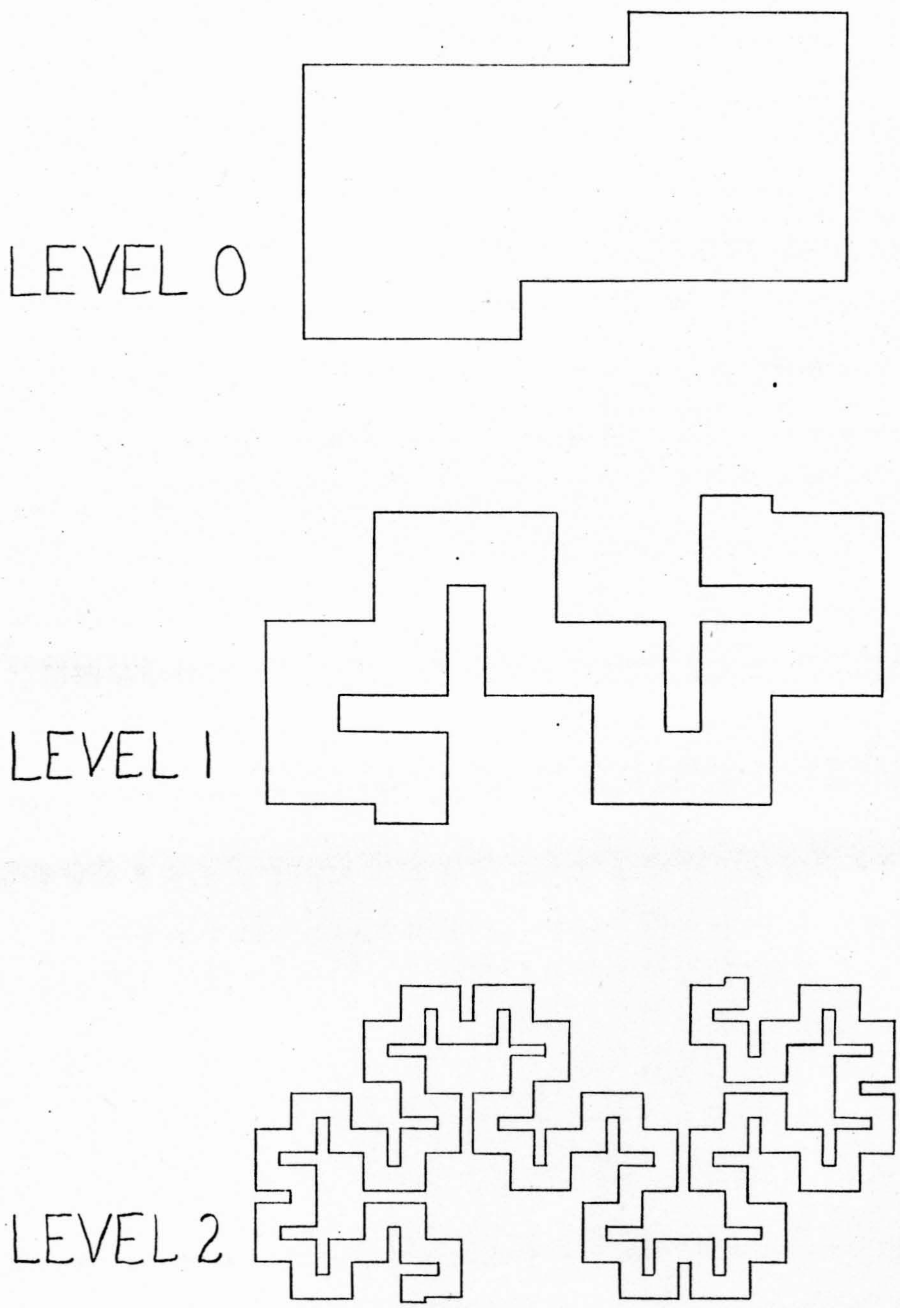


Figure 5

The outlines of the first three levels defined by level assignment to shapes generated by SG1 painting rules such that structurally equivalent parts of a shape are painted identically. If painting rules were based on shape equivalence (*e.g.* paint all squares identically) instead of structural equivalence, a determination of the shape of possible overlap configurations in a shape would be required.

Painting rules indicate how the areas contained in a shape are painted by considering the shape as a Venn diagram as in naive set theory. The terminals of each level in a shape are taken as the outline of a set in the Venn diagram. As parts of terminals may be assigned multiple levels, sets may have common boundaries. Levels 0, 1, 2, . . . are said to define sets L0, L1, L2, . . . respectively.

Painting rules have two sides separated by a double arrow. The left side of a painting rule defines a set using the sets determined by level assignment and the usual set operators, *e.g.* union ($\cup$), intersection ($\cap$), complementation ($\sim$), and exclusive or ($\otimes$). The sets defined by the left sides of the painting rules of M must partition the universal set. The right side of a painting rule is a rectangle painted in the manner the set defined by the left side of the rule is to be painted. The rectangle gives implicitly medium, color, texture, edge definition, etc. Because the left sides of painting rules form a partition, every area of the shape is painted in exactly one way. Using the set notation, all posible overlap configurations can be specified independent of shape. Any level in a shape may be ignored by excluding the corresponding set from the left sides of the rules.

The painting rules for the example are shown in Figure 6.

Because of the difficulty of printing areas of paint the convention of writing the color in the rectangle is used. The paint is assumed to be acrylic applied as flat, with high color density and hard edge. The effect of the painting rules in the example is to count set overlaps. Areas with three overlaps are painted yellow, two overlaps orange, one overlap red, and zero overlaps blue.

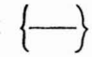
The limiting shape defines the size and shape of the canvas on which a shape is painted. Traditionally the limiting shape is a single rectangle, but this need not be the case. For example the limiting shape can be the same as the outline of the shape painted or it can be divided into several parts. Fried (1969) calls the limiting shape the "literal shape" and the shape on the canvas the "depicted shape". The limiting shape is designated by broken lines, and its size is indicated by an explicit notation of scale. The initial shape of the shape grammar in the same scale is located with respect to the limiting shape. The initial shape need not be located within the limiting shape. Informally, the limiting shape acts as a camera view finder. The limiting shape determines what part of the painted shape is represented on a canvas and in what scale.

The complete specification of the class of paintings shown in Figure 1 is given in Figure 6.

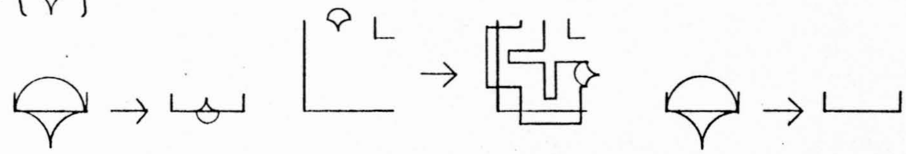
3.2 Sculpture

Sculpture is the material representation of three-dimensional shapes and is defined analogously to painting. A class of

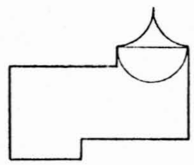
SHAPE GRAMMAR $SG1 = \langle V_T, V_M, R, I \rangle$

$V_T = \{$  $\}$ $V_M = \{$  $\}$

R CONTAINS:



I IS:



SELECTION RULE $\langle 0, 2 \rangle$

PAINTING RULES

$L0 \cap L1 \cap L2 \Rightarrow \boxed{\text{YELLOW}}$

$(L0 \cap L1) \otimes (L0 \cap L2) \otimes (L1 \cap L2) \Rightarrow \boxed{\text{ORANGE}}$

$L0 \otimes L1 \otimes L2 \Rightarrow \boxed{\text{RED}}$

$\sim(L0 \cup L1 \cup L2) \Rightarrow \boxed{\text{BLUE}}$

LIMITING SHAPE

10 INCHES

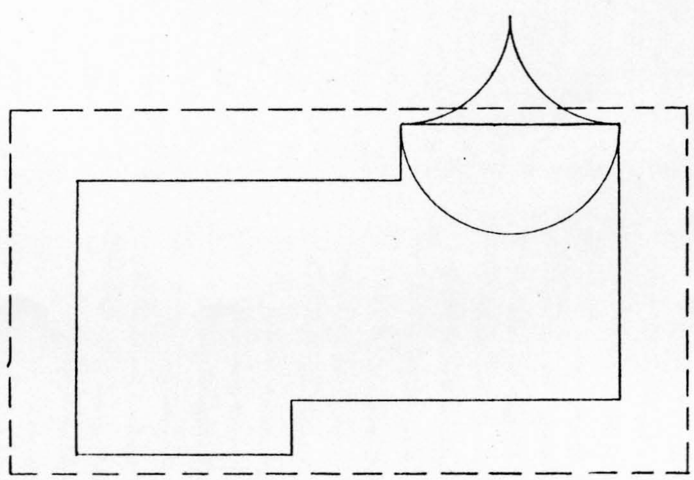


Figure 6
Complete, generative specification for the class of paintings containing Urform I, II, and III

sculptures 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 three-dimensional shapes, and a selection rule. M is a specification of material representations and consists of a finite list of sculpting rules and a limiting shape. Sculpting rules take the same form as painting rules with medium, surface, edge, etc., given implicitly in a rectangular solid. The limiting shape is three-dimensional.

4 Implications for Aesthetics and Design Theory

4.1 Aesthetics

Generative specifications of painting and sculpture have wide implications in aesthetic theory that regards the work of art as a coherent, structured whole. In this context, aesthetics proceeds by the analysis of that whole into its determinate parts toward a definition of the relationship of part to part and part to whole in terms of "unified variety" (Fechner, 1897), "order" and "complexity" (Birkhoff, 1932 and Eysenck, 1941), "a series of planned harmonies", "an internal organizing logic", "the play of hidden rules" (Focillon 1948), etc. The relationship between the wealth of visual information presented in a work of art and the parsimony of structural and material information required to determine the work of art seems central to this aesthetics. Wealth of visual information may be associated with "variety" and "complexity" and is taken to mean *visual complexity.* Parsimony of structural and material information may be associated with "order" and "an internal organizing logic" and is taken to mean *specificational simplicity.* Where visual complexity has been studied directly, *e.g.* (Attneave, 1957), specificational simplicity has necessarily been studied indirectly because no generative specifications of painting and sculpture have existed. Our specification of non-representational, geometric painting and sculpture with a structural component and a related material component provides for the direct study of the simplicity of the structural and material schema underlying the visual complexity of a work of art. Recent work on the complexity of grammars and the languages they define (Feldman *et.al.,* 1969) seems directly applicable. We believe that painting and sculpture that have a high visual complexity which does not totally obscure an underlying specificational simplicity make for good works of art. The use of the words "beautiful" and "elegant" to describe computer programs, mathematical theorems, or physical laws is in the spirit of this aesthetics——parsimonious specification supporting complex phenomena.

4.2 Design Theory

The formalism defined for the specification of painting and sculpture gives a complete description of a class of paintings or sculptures which is independent of the members of the class and is made in terms of a generative schema. For design theory in the visual arts this means that the definition and solution of design problems can be based on the specification of a work of art instead of the work of art itself. Generative specifications provide a well-defined means of expressing the artist's decisions about shapes and their organization and representation in the design of non-representational, geometric art. Once these decisions are made as to the relationships that are to underly a class of paintings or sculptures, a generative specification is defined and the structural and material consequences of the relationships are determined algorithmically. This enables the artist to obtain works of art with specificational simplicity and visual complexity which are faithful to these relationships and which would be difficult to design by other means.

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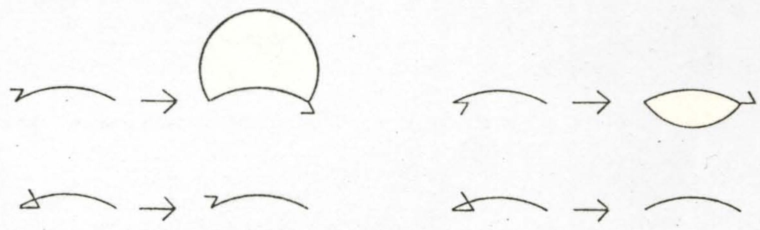
APPENDIX

Examples of painting and sculpture defined by generative specifications are shown in this section.

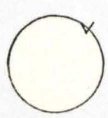
SHAPE GRAMMAR

$V_T = \{\frown\}$ $\quad V_M = \{\lrcorner\}$

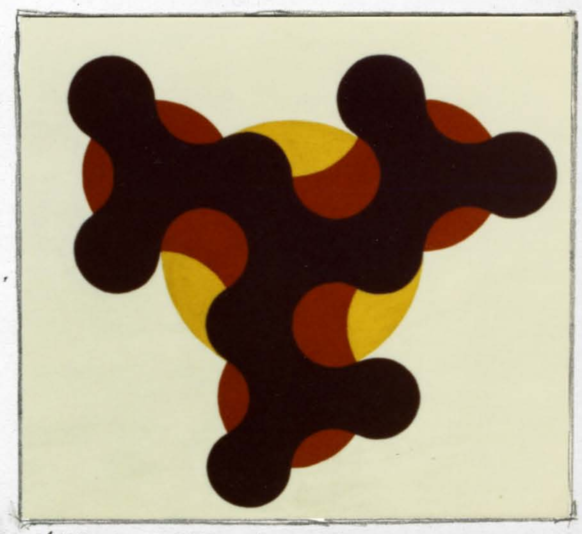
R CONTAINS:



I IS:



SELECTION RULE $\langle 2, 2 \rangle$

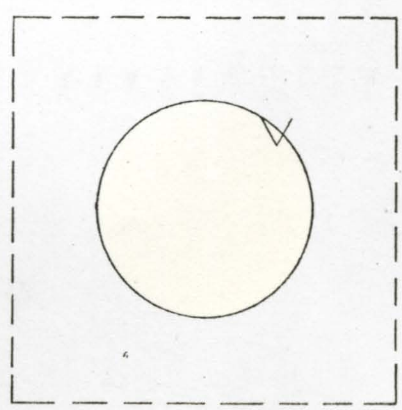


(Gips, 1970. Acrylic on canvas, 32 ins. X 32 ins.)

PAINTING RULES

L2	$\Rightarrow$	BLUE
$L1 \cap \sim L2$	$\Rightarrow$	RED
$L0 \cap \sim(L1 \cup L2)$	$\Rightarrow$	YELLOW
$\sim(L0 \cup L1 \cup L2)$	$\Rightarrow$	WHITE

LIMITING SHAPE



8 INCHES

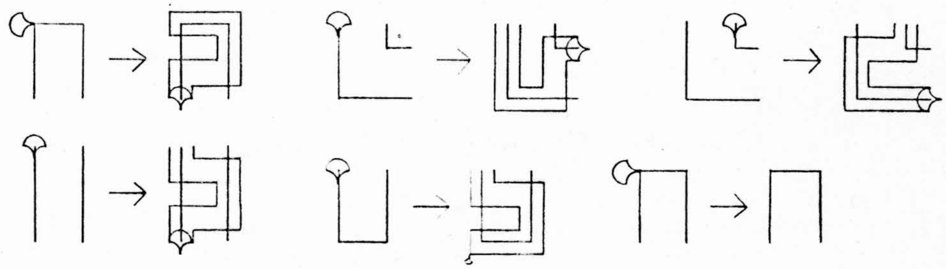
Figure 7
A class of paintings and its generative specification

Figure 8
(Stiny, 1968. Acrylic on canvas, each canvas 48 ins. X 48 ins., photographed in perspective.)
Variation of Peano's curve, specifications for this class
of paintings given in Figures 9 and 10.

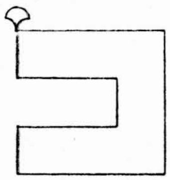
SHAPE GRAMMAR

$V_T = \{ — \}$ $V_M = \{$  $\}$

R CONTAINS:



I IS:



SELECTION RULE $\langle 0,2 \rangle$

PAINTING RULES

$L0 \cap L1 \cap L2 \Rightarrow$ $\boxed{\text{LIGHT GRAY}}$

$(L0 \cap L1) \otimes (L0 \cap L2) \otimes (L1 \cap L2) \Rightarrow$ $\boxed{\text{GRAY}}$

$L0 \otimes L1 \otimes L2 \Rightarrow$ $\boxed{\text{DARK GRAY}}$

$\sim(L0 \cup L1 \cup L2) \Rightarrow$ $\boxed{\text{BLACK}}$

LIMITING SHAPE

16 INCHES

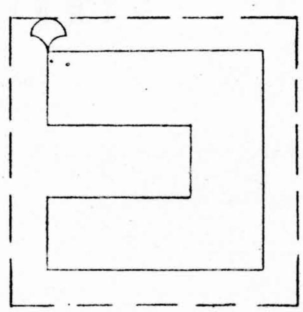
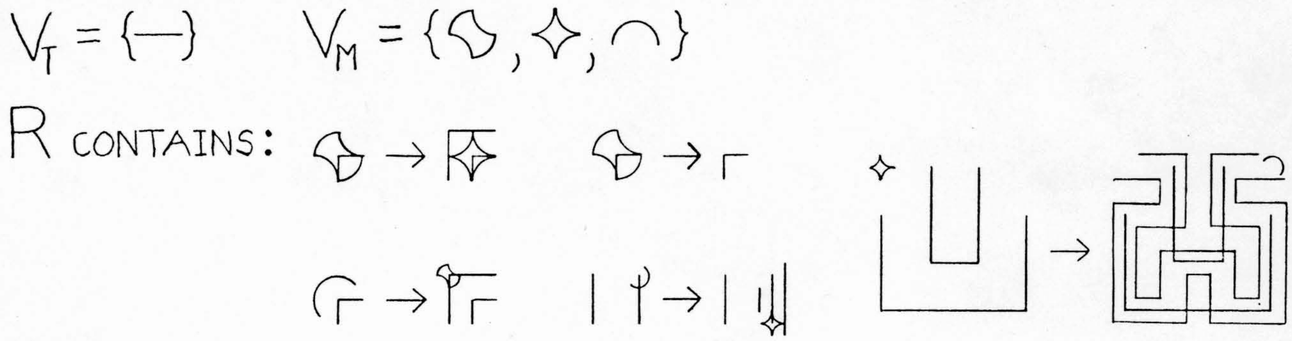
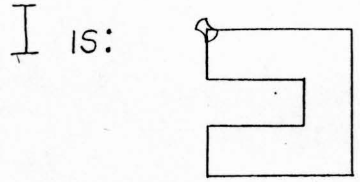


Figure 9
Complete, generative specification of the class of paintings in Figure 8
The shape grammar is based on a parsing which is faithful to Peano's original intentions, i.e. to pass a curve through every point in a square.

SHAPE GRAMMAR





SELECTION RULE ⟨0,2⟩

PAINTING RULES

$L0 \cap L1 \cap L2 \Rightarrow$ LIGHT GRAY

$(L0 \cap L1) \otimes (L0 \cap L2) \otimes (L1 \cap L2) \Rightarrow$ GRAY

$L0 \otimes L1 \otimes L2 \Rightarrow$ DARK GRAY

$\sim(L0 \cup L1 \cup L2) \Rightarrow$ BLACK

LIMITING SHAPE

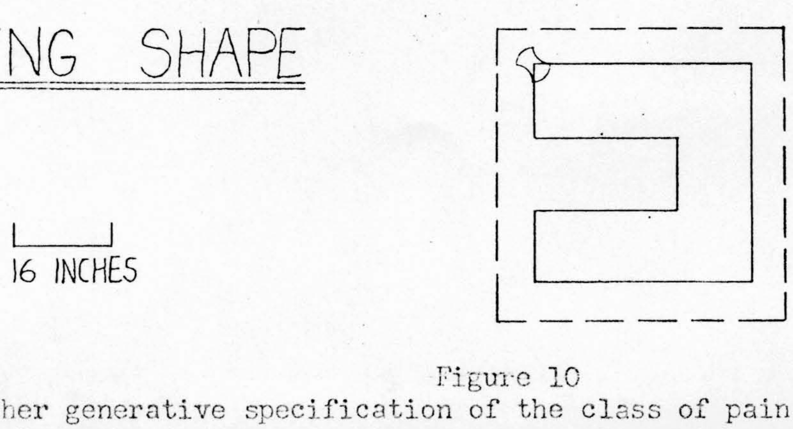
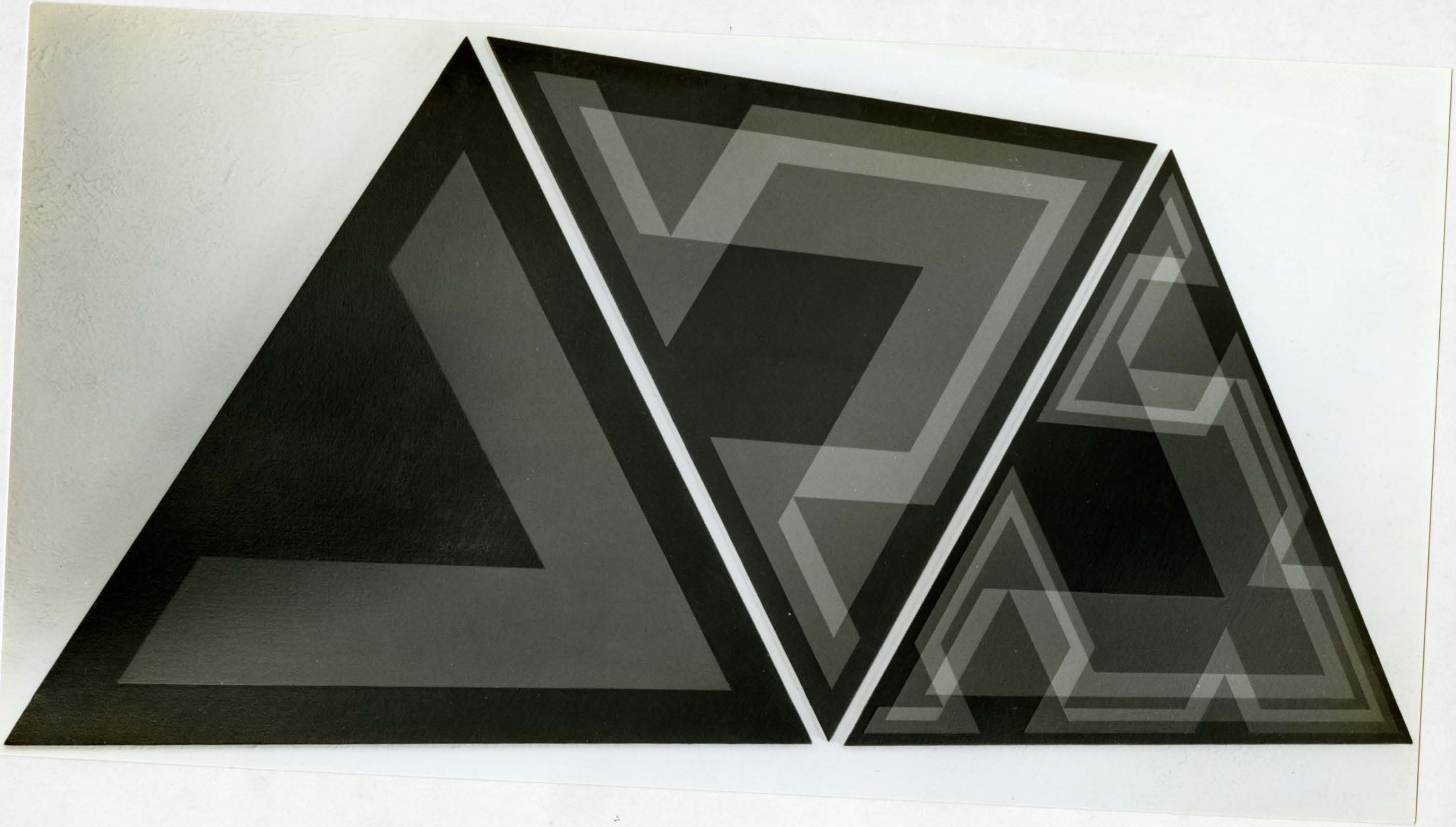
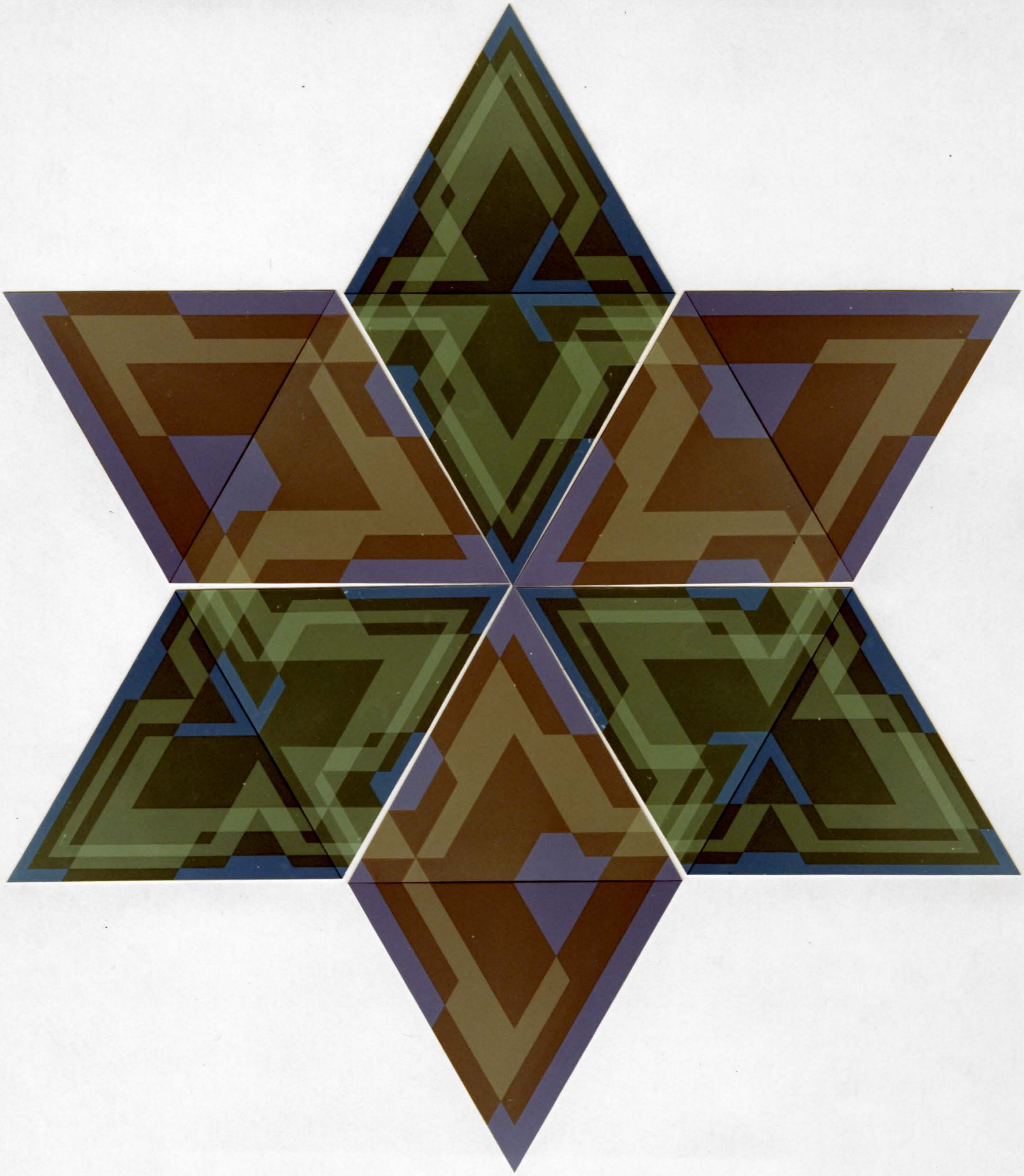


Figure 10
Another generative specification of the class of paintings in Figure 8
The shape grammar is based on a parsing which superimposes "凹"'s on the vertices of "凹"'s in such a way that each level of "凹"'s is connected.



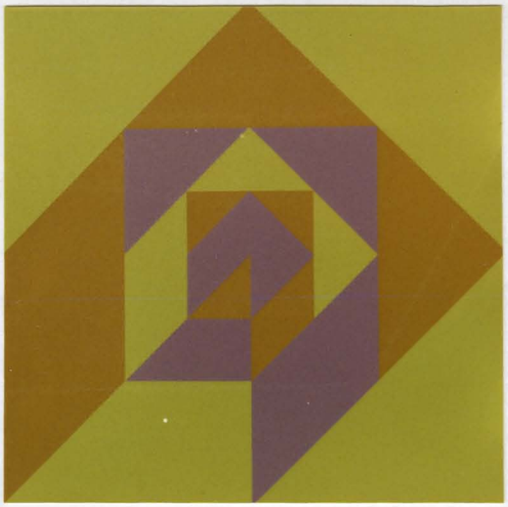
(Stiny, 1968. Acrylic on canvas, each canvas 36 ins. per side, photographed in perspective.)



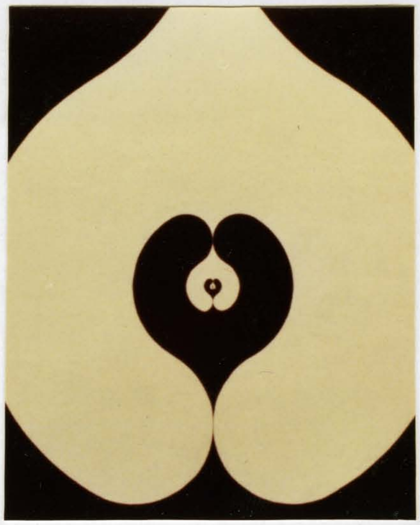
Bloom's Day
(Stiny, 1969. Acrylic on canvas, 12 canvases, 108 ins. X 125 ins.)

Figure 11, page 2

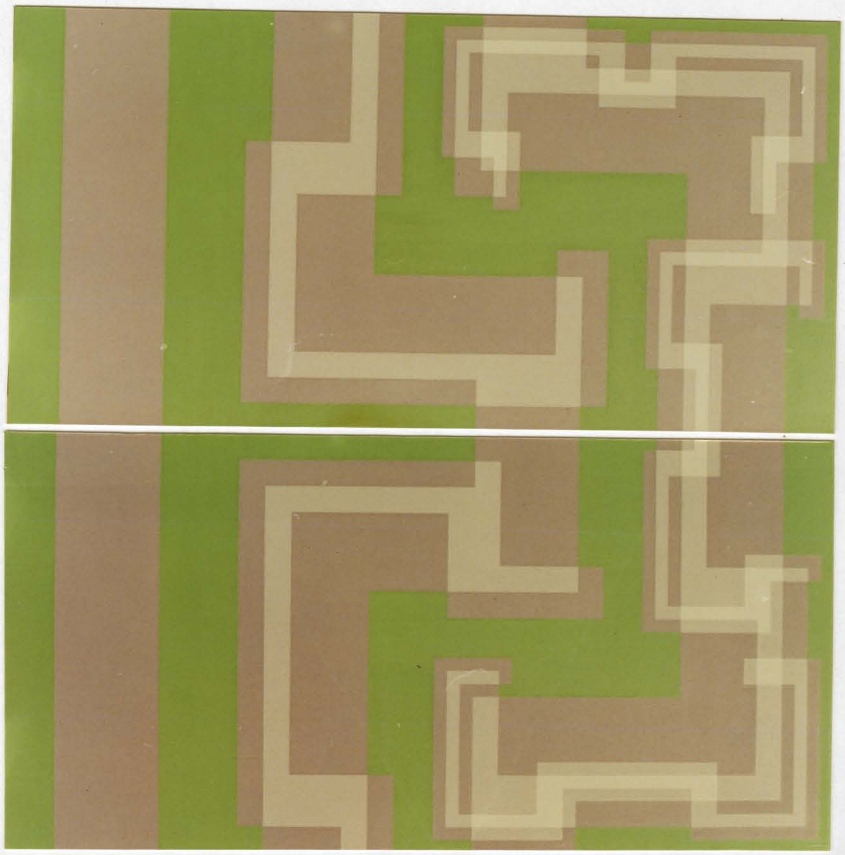
Note that the colors of the alternating diamonds are different due to the photo development process. In the real painting the colors are uniformly blue and grey. -- JEG, August 2009



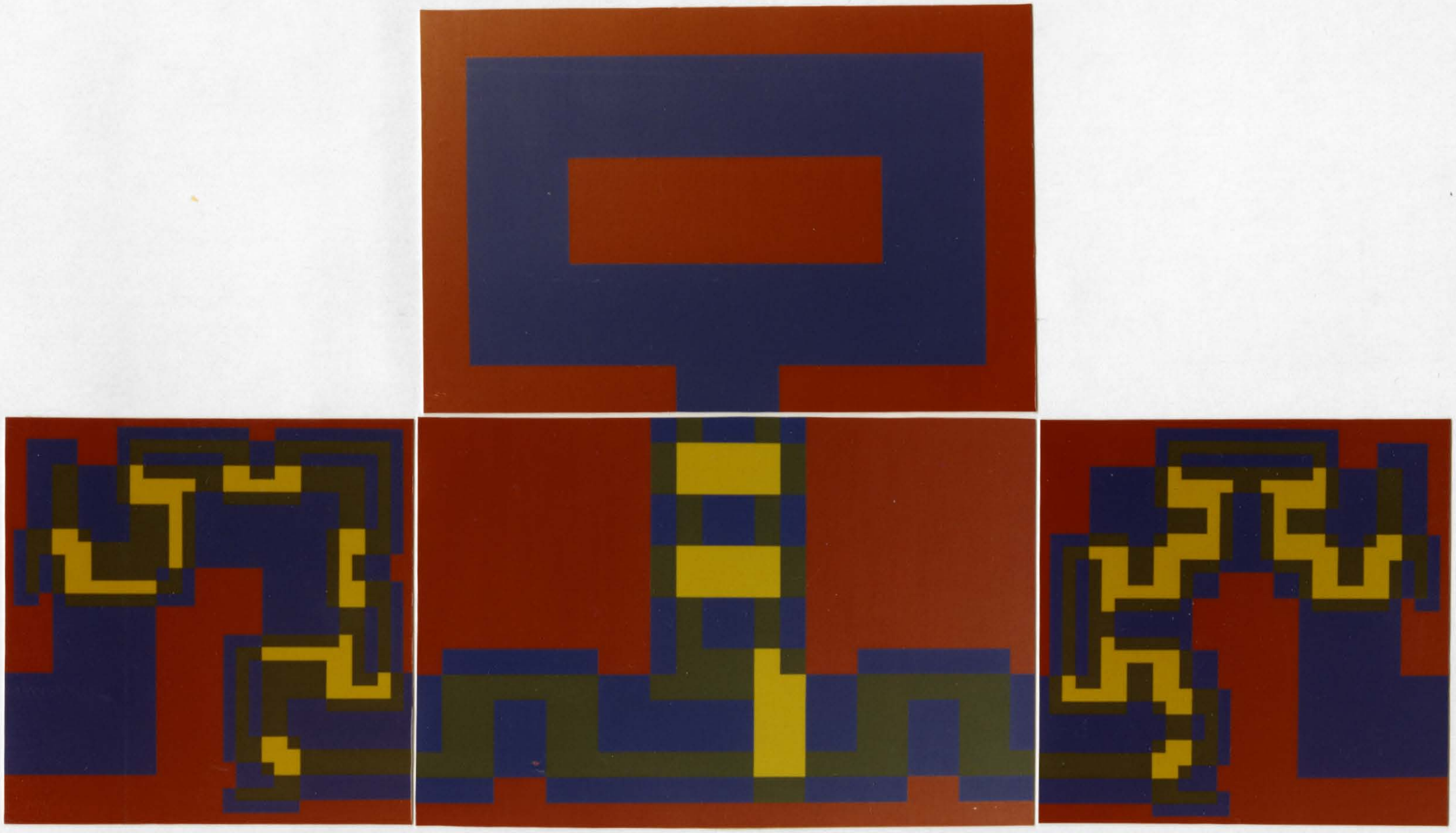
(Stiny, 1969. Acrylic on canvas, 32 ins. X 32 ins.)



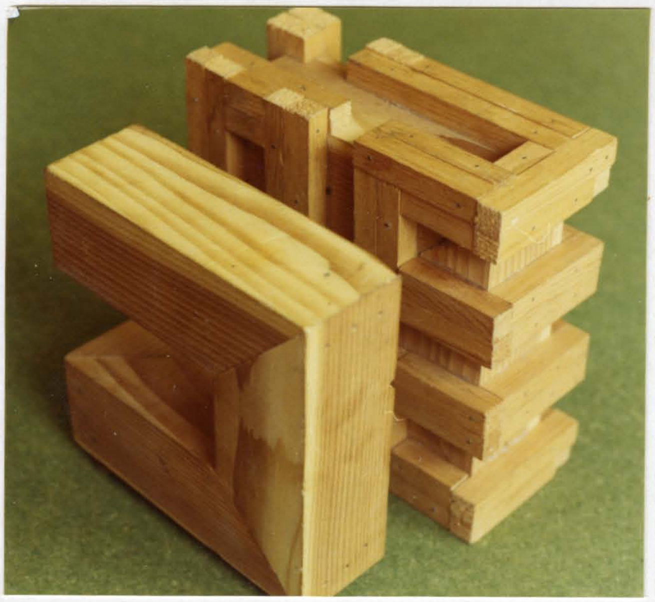
(Gips, 1969. Acrylic on canvas, 24 ins. X 30 ins.)



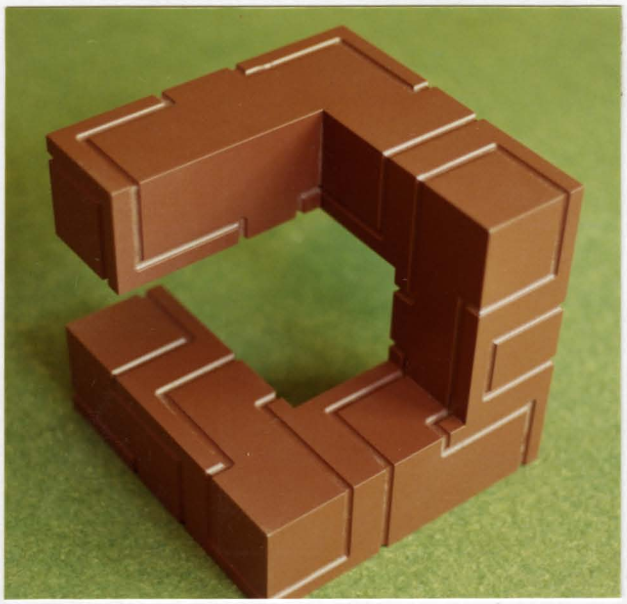
(Stiny, 1970. Acrylic on canvas, 2 canvases, 72 ins. X 72 ins.)



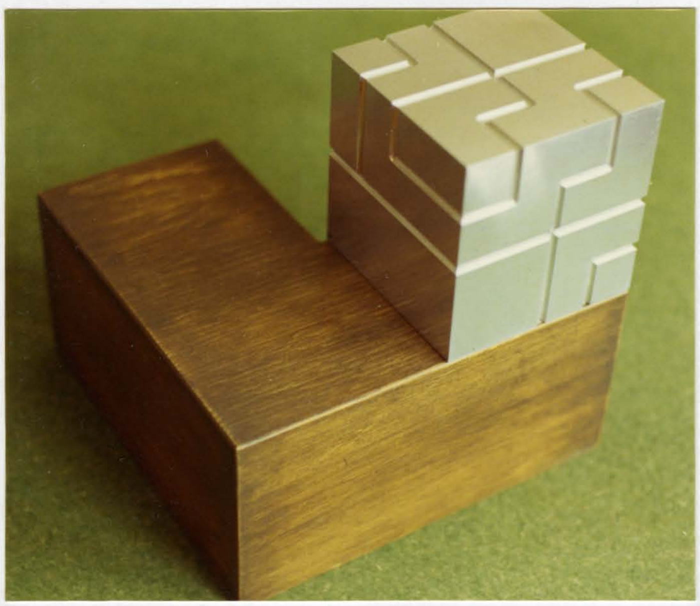
(Stiny, 1969. Acrylic on canvas, 4 canvases, 60 ins. X 120 ins.)



(Stiny, 1969. Redwood mock-up, 6 ins. X 6 ins. X 6 ins.) Three-dimensional variation of Peano's curve.



. . . lines, lines wind around, wind around . . . (Stiny, 1970. Painted steel, 6 ins. X 6 ins. X 6 ins.)



Nescient Matter (Stiny, 1970. Aluminum and wood, 8 ins. X 8 ins. X 8 ins.)

Figure 12
Sculptures defined by generative specifications