Emergence of Shape Semantics of Architectural Shapes

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Abstract. This paper presents a representation of shapes and shape semantics and processes for the emergence of shape semantics. Constraints on the behaviours of shapes are used to define shape semantics, in particular visual symmetry and visual rhythm A process model of emergence of shape semantics which relies on this representation is developed. Discovery of symmetry in architectural plans is demonstrated.

1 Introduction

Drawn shapes play a critical role not only in representing a design concept but also in allowing the designer to reinterpret them to develop new ideas. In the conceptual and creative aspects of designing this reinterpretation of what has been drawn appears to play an important role (Schön, 1983). Working in some visual medium - drawing - the designer sees what is there, draws in relation to it, and sees what has been drawn, thereby informing further designing. In all this seeing, the designer not only visually registers information but also constructs and discovers its meaning - identifies patterns. Emergence of shape semantics is the phenomenon of making explicit meaningful visual patterns which were not explicitly indicated, by grouping explicit or implicit structures of objects in defined ways. In this paper we define visual patterns from shapes as *shape semantics* when the patterns are grouped into predefined labelled categories. There is a wide variety of reinterpretations possible. Emergence of shape semantics in design plays an important role in organising decisions, providing order, and generating the final form of design results from a designer's interpretation of drawings.

When we think of designing as a conversation with materials conducted in the medium of drawings and crucially dependent on seeing, we note that current CAAD systems are unable to aid the designer in the manipulation of visual patterns and in the recognition of emergent structures because they are not represented. Current CAAD systems have limitations in the interpretation of shapes to capture visual patterns from shapes which are perceivable by human beings. This is one obstacle in using computers to provide assistance to human creativity. Thus the major aim of this paper is to build

computational models for emergence of shape semantics and thus to improve the capability of CAAD systems.

Symbolic models related to shapes and shape emergence have been presented by Stiny (1980; 1985; 1993) and by Krishnamurti (1980; 1981). A computational model for shape emergence has been developed by Gero (1992), Gero and Yan (1993, 1994) and Liu (1993). However, there has been little work dealing with emergence of shape semantics at a symbolic, computational level. Interest in shape semantics is found in Schön's work (Schön and Wiggins, 1992) and in the work of Masaki, Gero and Purcell (1997): the designer not only visually registers information but also constructs meanings of shapes - identifies patterns and gives them meanings beyond themselves during the design process. In psychology, the laws of perception in Gestalt theory have been used for figure perception (Arnheim, 1966). Some principles from these laws of perception can be applied to perceive shape semantics in architectural designs (Meiss, 1986). Clark and Pause (1985) analysed existing architectural designs and classified the drawings into formative ideas. Some of these formative ideas match the concepts in shape semantics described in this paper. Recently, Gero and Jun (1995a, 1995b) have developed symbolic representations of shape semantics.

In this paper we present a contribution which assists in the discovery of shape semantics. It is concerned with a general process model of emergence of shape semantics. We wish to discover emergent shape semantics derivable from the initial two dimensional shapes.

2. Shape Semantics

2.1 Definitions

From seeing what was intended to be drawn, intentional and/or unintentional patterns of shapes are identified. The patterns can be grouped into dominant themes or formative ideas which can conceivably be used in the generation of designs when designers want to adapt the patterns for designing. A formative idea is understood to be a concept which a designer can use to influence or give form to a design. The ideas provide ways to organize decisions, to provide order and to consciously generate form. Two types of shape semantics are dealt with. A *primary shape semantics* is a predefined visual pattern of relationships of shapes which is represented explicitly and intentionally by designers for their own purpose. An *emergent shape semantics* is a predefined visual pattern of shapes that exists only implicitly in the relationships of shapes, and is never explicitly input and is not represented at input time.

Gero and Yan (1994) give the following definitions.

A **primary shape** *is a shape that is initially represented explicitly and thus can be input and manipulated by specifying its behaviours.*

An **emergent shape** *is a shape that exists only implicitly in a primary shape and is never explicitly input and is not represented at input time.*

A **polyline shape** *is composed of a set of straight lines.*

A **bounded polyline shape** *is an enclosed polyline shape, for any point on the boundary of which there exists at least one circuit composed of line segments which start from and end at the point without covering any line segment more than once,*

A **shape** *(in this paper) is a bounded polyline shape.*

Figure 1(a) shows examples of primary shapes, primary shape semantics (symmetries) in Figure 1(b) and emergent shape semantics in Figure 1(c). *Shape semantics emergence* is the process of recognizing emergent shape semantics and primary shape semantics from primary shapes and /or emergent shapes.
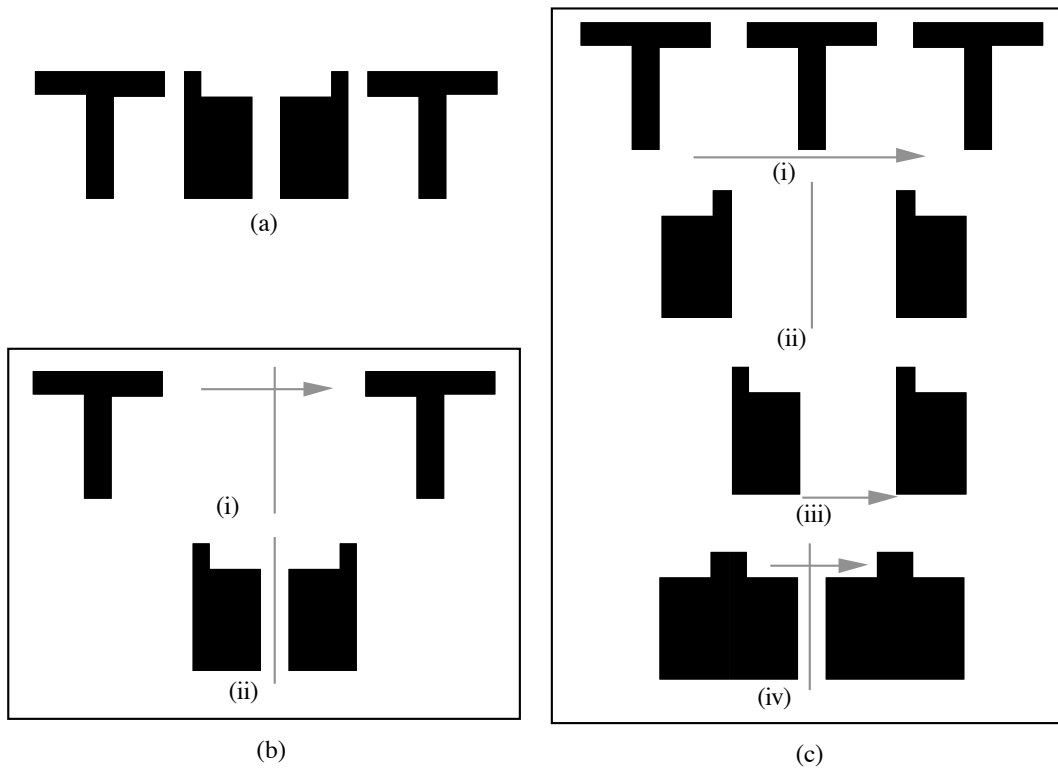

Figure 1: (a) Primary shapes, (b) primary shape semantics; (i) primary T shape reflectional symmetry or translational symmetry and (ii) primary L shape reflectional symmetry and (c) examples of emergent shape semantics; (i) emergent three T shapes translational symmetry, (ii) emergent reflectional symmetry, (iii) emergent L shape
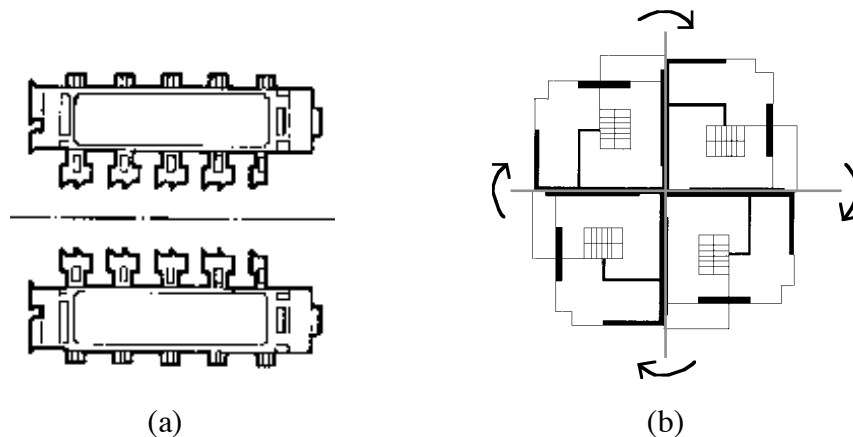
translational symmetry and (iv) emergent reflectional symmetry or translational symmetry.

2.2 Shape semantics from architectural drawings

Visual similarities appear in many architects' works, independent of time, style, location, function or type of building. These visual similarities can be conceptualized and predefined into various architectural shape semantics which play a dominant role in generating building designs. There are many types of shape semantics in architectural design but here we deal with only four types of shape semantics of architectural designs through interpretations of the visual patterns from plans and facades: visual symmetry, visual rhythm, visual movement and visual balance.

2.2.1 Visual symmetry

Visual symmetry has been used extensively from ancient architecture to modern times. An object is defined as symmetrical to the extent that it satisfies symmetry operations such as isometric transformation: translation, reflection, rotation and composition of these (Mitchell, 1990). Each type of symmetry has been used for various purposes in different buildings. Figure 2(a) shows emergence of reflectional symmetry. Two buildings are reflected by a symmetrical axis.
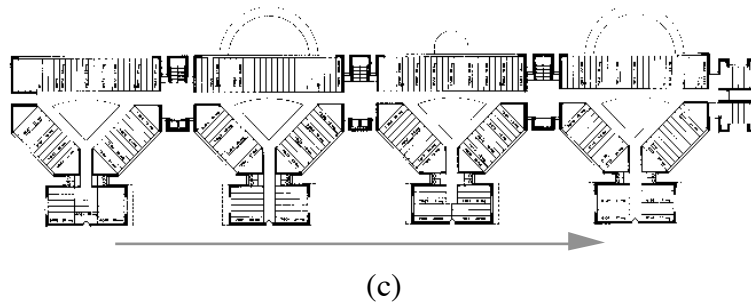

(a)   (b)

(c)

Figure 2: Emergence of symmetry in architectural plans: (a) reflectional symmetry: Salk Institute (Louis Kahn, 1959-1965); (b) rotational symmetry: Suntop Homes (Frank Lloyd Wright); (c) translational symmetry: Project for the new offices of the Bank of Gothard in Lugano (Mario Botta, 1982).

Figure 2(b) illustrates rotational symmetry in the plan for Suntop Homes in which four identical apartments are rotated through 90° to one another. Translational symmetry is shown in Figure 2(c).

2.2.2 *Visual rhythm*

Visual rhythm in shapes is the patterns of relationships of equivalent shapes or groups of shapes in which the patterns are formed by regular repetitions along one or more axes. Therefore, the emergence of visual rhythm of architectural shapes may be discovered when regular repetitions of visual patterns of equivalent shapes exist. Figure 3(a) exemplifies the regular repetition of a unit shape (rectangle) in certain directions. Many examples of visual rhythm can be emerged from the facade of the Concours for 800 apartments at Strassburg as shown in Figure 3(b).
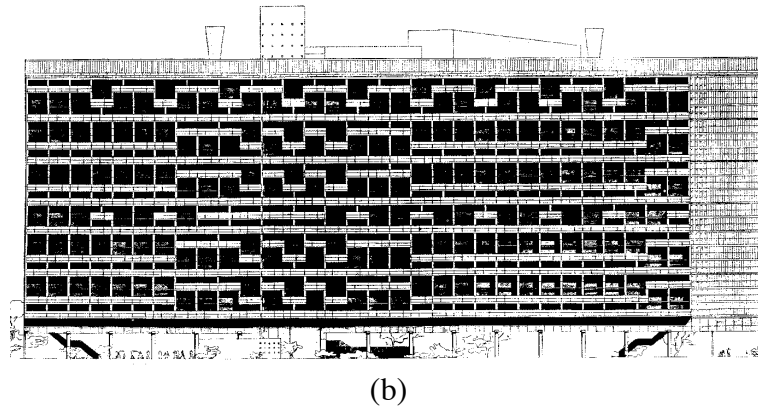

(a)

(b)
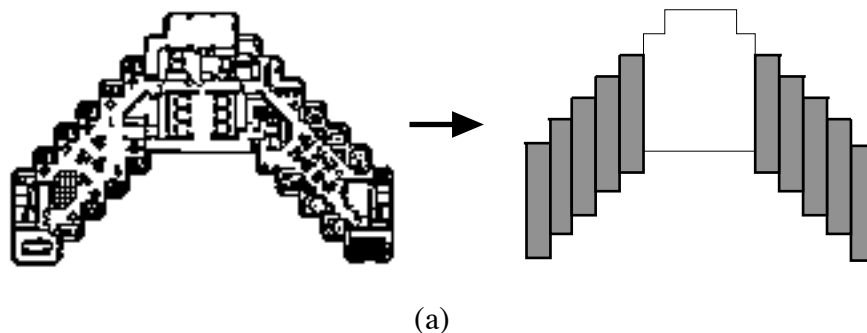
Figure 3: Emergence of visual rhythm in architectural plans: (a)Akasaka Prince Hotel (Kenzo Tange, 1972-1982); (b) the facade of the Concours for 800 apartments at Strassburg (Le Corbusier, 1951).

2.2.3 Visual movement

Visual movement is recognised when incremental changes of an attribute of structure occur in space as well as in form. Visual movement in architectural design is discovered when groups of similar or proximate shapes occur with some regularity. Visual movement is defined as a pattern of relationships of equivalent or similar shapes or groups of shapes such that the pattern contains a transformed or regular repetition along one or more axes. Figures 4(a) and 4(b) show that similar shapes are grouped in size. Visual movement emerges in the direction from larger shapes to smaller shapes, in general.
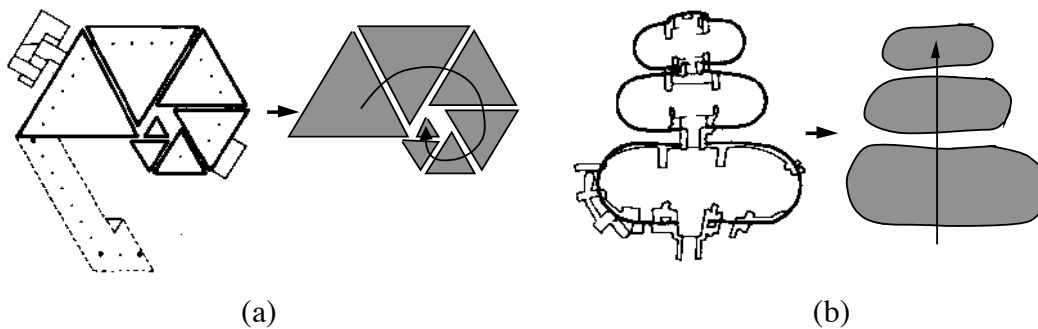

(a)   (b)

Figure 4: Emergence of visual movement in architectural plans: (a) Holy Trinity Ukrainian Church (Radoslav Zuk, 1977); (b) Temple in Tarxien (Unknown, 2100BC-1900BC).

2.2.4 Visual balance

Visual balance is recognised when a structure has perceptual or conceptual equivalent weight on either side of an axis of balance. In general, balance is classified into two

kinds: visual balance and conceptual balance. Only visual balance is described here. Figure 5(a) exemplifies the essence of the idea of balance by geometry with two complete and different geometric forms. Figure 5(b) shows that a new extended building is balanced by the older building along a balance axis.
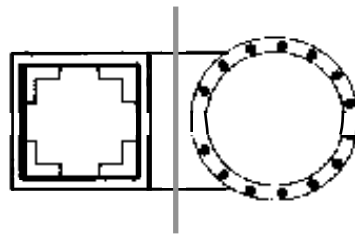
Figure 5: Emergence of visual balance in architectural plans: (a) Architectural Setting (Donato Bramante, 1473); (b) Olivetti Training School (James Stirling, 1969).

3. Symbolic Representation of Shape Semantics

3.1 A symbolic representation for shapes

3.1.1 Introduction

Using infinite maximal lines as representative primitives, the general form of the symbolic representation of shapes is (Gero, 1992; Gero and Yan, 1994)

$$S = \{ N_l ; \text{constraints}\}$$

where N_l is the number of infinite maximal lines constituting shape S and the constraints, which constrain behaviours or properties resulting from the infinite maximal lines, based upon which particular shapes are defined.

3.1.2 Constraints on infinite maximal lines

Three classes of constraints on infinite maximal lines are summarised from Gero and Yan's work (1994): geometrical constraints on slopes, topological constraints on intersections, and dimensional constraints on the lengths of line segments.

1. Geometrical constraints

The parallelarity on any l_i and l_j is denoted as $l_i // l_j$.

The perpendicularity on any l_i and l_j is denoted as $l_i \perp l_j$.

The skewness on any l_i and l_j is denoted as $l_i \times l_j$.

The coincidence on any l_i and l_j is denoted as $l_i = l_j$.

Where l denotes an infinite maximal line.

Intersection i_{jk} is implied by geometrical properties of infinite maximal lines. The order of the subscripts of i_{jk} is not significant, i.e. i_{jk} and i_{kj} represent the same intersection.

$$l_j \times l_k => i_{jk}.$$

$$l_j \perp l_k => i_{jk}.$$

Where A => B means A implies B.

However, i_{jk} does not exist if $l_j // l_k \ \vee \ l_j = l_k$.

2. Topological constraints

There are three kinds of intersection groups (Gero and Yan, 1994): ordinary groups, adjacent groups, and enclosed groups.

a. An ordinary group is represented by a pair of parenthesis, "(" and ")", in which any two intersections in the group represents a line segment. The order of intersections in this group is of no significance.

b. An adjacent group is represented by a pair of angle brackets, "⟨" and "⟩", in which only two adjacent intersections can represent a line segment. The order of intersections in this group is significant.

c. An enclosed group is represented by a pair of square brackets, "[" and "]". An enclosed group represents a circuit of line segments, i.e., a bounded polyline shape.

3. Dimensional constraints

The dimensional property is the length of a line segment which embeds in an infinite maximal line. The segment which is defined by its bounding two intersections is represented as (i_{jk}, i_{jp}). The segment, (i_{jk}, i_{jp}), is embedded in the infinite maximal line l_j. The length of a segment (i_{jk}, i_{jp}) is represented as $d(i_{jk}, i_{jp})$. Examples of dimensional constraints are:

two line segments are of equal length, $d(i_{jk}, i_{jp}) = d(i_{js}, i_{jr})$;

one line segment's length is k times that of another, $d(i_{jk}, i_{jp}) = kd(i_{js}, i_{jr})$.

3.1.3 Features of properties

1. Features of intersections.

a. i_{jk} is equivalent to i_{kj}.

b. i_{ij} and i_{ik} are called collinear intersections in l_i .

c. i_{ijk} exists when l_i, l_j and l_k are concurrent.

2. Features of segments.

a. The midpoint of a segment , (i_{jk}, i_{jp}), is represented as $i_{(i_{jk}, i_{jp})M}$:

$\exists\, i_{jr} \in (i_{jk}, i_{jp})\ \wedge\ d(i_{jk}, i_{jr}) = d(i_{jr}, i_{jp})$

$=> i_{jr}$ becomes $i_{(i_{jk}, i_{jp})M}$,

where i_{jr} denotes any intersection within an infinite maximal line, l_j.

b. The perpendicular bisector of a segment, (i_{jk}, i_{jp}), is represented as $l_M^{(i_{ij}, i_{pq})}$:

$\exists\, i_{(i_{jk}, i_{jp})M}\ \wedge\ (i_{jk}, i_{jp}) \perp l_m => l_m$ becomes $l_M^{(i_{ij}, i_{pq})}$.

l_m is an infinite maximal line passing through a midpoint of a segment. There is an infinite number of l_ms. On the other hand, l_M is an infinite maximal line perpendicularly passing through a midpoint of a segment. There is only one l_M.

3.2 A symbolic representation for shape semantics

3.2.1 Introduction

The general symbolic representation of shape semantics constructed of shapes is

$$\Im = \{N_s; \text{ constraints}\}$$

where N_s is the number of shapes involved in the shape semantics $\Im$ and the constraints, which constrain behaviours or properties resulting from the shapes, based upon which particular shape semantics are defined.

3.2.2 Visual symmetry

When the constraints on shapes are isometric transformational constraints, a class of symmetry exists. Therefore the symbolic representation of symmetry, denoted as **S**, is

$$S = \{N_s \ ; \ C_i\}.$$

where C_i are isometric transformational constraints.

There are four types of constraints on isometric transformations (Baglivo and Graver, 1983) in dealing with symmetry: translational constraints (denoted by τ), rotational constraints (denoted by σ), reflectional constraints (denoted by ρ), and glide reflectional constraints (denoted by γ). Thus, the symbolic representation of symmetry can be extended into

$$S = \{N_s \ ; \ \tau, \ \sigma, \ \rho, \gamma\}.$$

Whenever symmetry is discovered, there is an isometric operator (denoted by φ). Therefore the following reasoning is possible.

$\varphi(S_i) = (S_j) \ <=> $ Symmetry exists between S_i and S_j.
Where $<=>$ means logical equivalence.

For example, let l_i, l_j, l_k belong to S_i and l_p, l_q, l_r belong to S_j. The representation of two primary triangles is

$S_i = \{3; [i_{ij}, i_{ik}, i_{jk}]\},$
$S_j = \{3; [i_{pq}, i_{pr}, i_{qr}]\}.$

Transformational relationships are implied when $\varphi(S_i) = (S_j)$ exists.

$\varphi(S_i) = (S_j) \ => \varphi(\text{one of } ls \in S_i) = (\text{one of } ls \in S_j),$

$$\varphi(S_i) = (S_j) \Rightarrow \varphi(\text{one of } is \in S_i) = (\text{one of } is \in S_j).$$

Let the following corresponding infinite maximal lines and corresponding intersections be inferred when $\varphi(S_i) = (S_j)$.

Corresponding infinite maximal lines:
$$l_i \leftrightarrow l_p, \, l_j \leftrightarrow l_q, \, l_k \leftrightarrow l_r.$$
Corresponding intersections:
$$i_{ij} \leftrightarrow i_{pq}, \, i_{ik} \leftrightarrow i_{pr}, \, i_{jk} \leftrightarrow i_{qr}.$$

Isometric transformational constraints concern the structures within which corresponding infinite maximal lines and corresponding intersections are organised. They are represented as groups of corresponding intersections or topological properties of segments consisting of corresponding intersections.

1. Translational constraint (τ)

The translational constraint makes use of the concept of constructed segments. *Constructed segments* are segments constructed between corresponding intersections. Let i_{ab} corresponds to i_{cd}. The constructed segment is implied and represented as follows:

$$i_{ab} \leftrightarrow i_{cd} \Rightarrow c(i_{ab}, i_{cd}).$$

In the above example three constructed segments are inferred from corresponding intersections as follows:

$$i_{ij} \leftrightarrow i_{pq} \Rightarrow c(i_{ij}, i_{pq}),$$
$$i_{ik} \leftrightarrow i_{pr} \Rightarrow c(i_{ik}, i_{pr}),$$
$$i_{jk} \leftrightarrow i_{qr} \Rightarrow c(i_{jk}, i_{qr}).$$

Given two congruent shapes, translational symmetry exists when any group of two constructed segments which are decomposed into four corresponding intersections forms part of a parallelogram. The other two sides of the parallelogram must be the corresponding sides from each of the two congruent shapes (Baglivo and Graver, 1983) as shown in Figure 6,
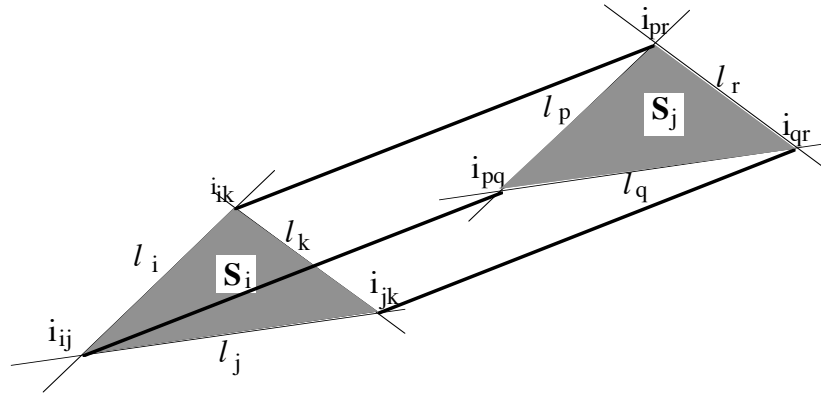
Figure 6: Translational symmetry constraint represented graphically

2. Reflectional constraint (ρ)

Given two congruent shapes, reflectional symmetry exists when a group of two constructed segments which are decomposed into four corresponding intersections forms the parallel pair of lines of a trapezoid. The other two sides of the trapezoid must be the corresponding sides from each of the two congruent shapes and the midpoints of constructed segments are collinear (Jenkins, 1983) and perpendicular bisectors of all constructed segments are coincident (March and Steadman, 1974; Baglivo and Graver, 1983). Figure 7 illustrates the constraints for reflectional symmetry and the midpoints of constructed segments are collinear. This implies that the perpendicular bisectors of all constructed segments are coincident. The axis of reflection, L, is regarded as the perpendicular bisectors of all constructed segments. Figure 7 shows the axis of reflectional symmetry.
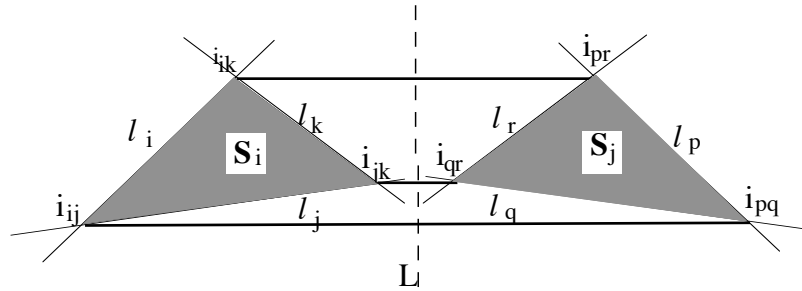

Figure 7: Reflectional symmetry constraint represented graphically

3. Rotational constraint (σ)

Given two congruent shapes, rotational symmetry exists when the perpendicular bisectors of all constructed segments are concurrent (March and Steadman, 1974; Baglivo and Graver, 1983), as shown in Figure 8. The concurrency point is the rotational centre.

4. Glide reflectional constraint (γ)

Given two congruent shapes, glide reflectional symmetry exists when the midpoints of constructed segments connecting corresponding intersections in the two congruent shapes are collinear and perpendicular bisectors of all constructed segments are not coincident (March and Steadman, 1974; Baglivo and Graver, 1983) as shown in Figure 9.
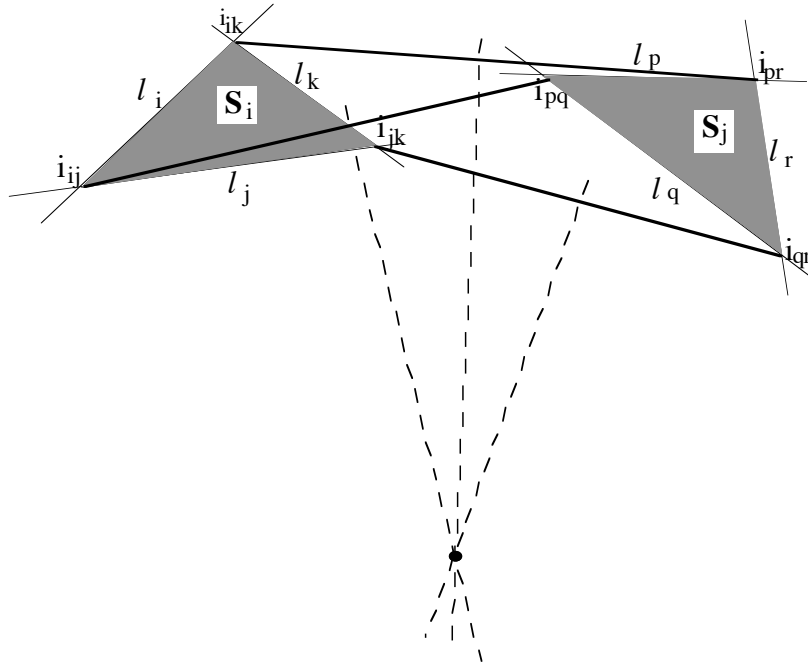

Figure 8: Rotational symmetry constraint represented graphically

Figure 9: Glide reflectional symmetry constraint represented graphically

3.2.3 Visual Rhythm

Visual rhythm is defined as a pattern of relationships of equivalent objects or groups of objects such that the pattern contains a regular repetition along one or more axes. An object may be a single line segment, a shape or a group of line segments. Therefore, the emergence of visual rhythm may be discovered when such repetitions of visual patterns of objects can be found.

Equivalent objects or equivalent groups of objects are treated as the unit of visual rhythm when the units are repeated. The group, G, is represented by the number of objects (n_o), number of constraints (n_c) and constraints on units.

$$G = n_o \, (n_c; \text{constraints on units}).$$

Therefore, the representation of visual rhythm becomes a special case of the general expression for shape semantics, ie

$$\boldsymbol{R} = N_g \, (N_c; C_r)$$

where $\boldsymbol{R}$ denotes visual rhythm, N_g is the number of groups which produce the repeating patterns, N_c is the number of constraints and C_r is the rhythm constraints on groups. For generality a group may contain a single line segment, a single enclosed shape, a group of line segments or a group of enclosed shapes.

1. Constraints

Five symbols, $\rightarrow$, $\uparrow$, $\downarrow$, $\nearrow$ and $\searrow$, are used to represent topological constraints on objects in visual rhythm here (Gero and Jun, 1995a), many other constraints are possible. These five describe the following topological constraints on objects.

O_1 is left of O_2, ie, $\tau(O_1) = O_2 \Rightarrow O_1 \rightarrow O_2 \Rightarrow O_2$ is right of O_1.

O_1 is below O_2, ie, $\tau(O_1) = O_2 \Rightarrow O_1 \uparrow O_2$.

O_1 is above O_2, ie, $\tau(O_1) = O_2 \Rightarrow O_1 \downarrow O_2$.

O_1 is below left of O_2, ie, $\tau(O_1) = O_2 \Rightarrow O_1 \nearrow O_2. \Rightarrow O_2$ is above right of O_1.

O_1 is above left of O_2, ie, $\tau(O_1) = O_2 \Rightarrow O_1 \searrow O_2 \Rightarrow O_2$ is below right of O_1.

Where O_i denotes objects and $\tau(O_i) = O_j$ means O_i is translated into O_j.

For example, $\boldsymbol{R} = N_g \, \{N_c; (G\rightarrow)\}$ represents N_g identical groups translated from left to right N_c times. For simplicity we will write this as $\boldsymbol{R} = N_g \, \{N_c \, (G\rightarrow)\}$ eliding the ";". When a group is a group of enclosed shapes, the same symbols are used for topological constraints on shapes. Figure 10(b) shows a visual rhythm represented by $\boldsymbol{R} = 5\{4 \, (G\rightarrow)\}$. Representation of the group as shown in Figure 10(a) is defined as follows:

$G = 3(\rightarrow, \searrow)$

$\Rightarrow S_1 \rightarrow S_2 \searrow S_3$

$\Rightarrow \tau_1(S_1) = S_2$ and S_1 is left of S_2 $\wedge$ $\tau_2(S_2) = S_3$ and S_2 is above left of S_3
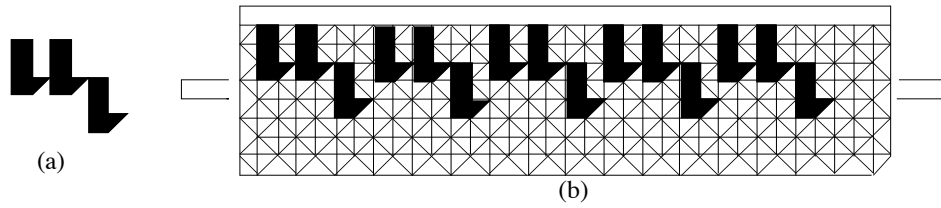
Figure 10: Visual rhythm discovered in a facade (a) grouping of units, and (b) the discovered visual rhythm.

2. Examples

Various types of visual rhythm as repeating units of group of enclosed shapes are shown in Figure 11. The representation of each type of visual rhythm shown in Figure 11 is as follows:

Figure 11(a):

Unit = ,

Group of units: G = 7(2→, ↓, 2→, ↑),

Representation of visual rhythm: R = 2[3{2(G→)} ↓];

Figure 11(b):

Unit = ,

Group of units: G = 2(↘),

Representation of visual rhythm: R = 2[4{3(G↘)} ↘];

Figure 11(c):

Unit = ,

Group of units: G = 3(2↘)

Representation of visual rhythm: R = 8{7(G→)};

Figure 11(d):

Unit =

,

Group of units: G = 8(4↘, 3↗),

Representation of visual rhythm: R = 4{3(G→)}.

(a)

(b)

(c)

(d)
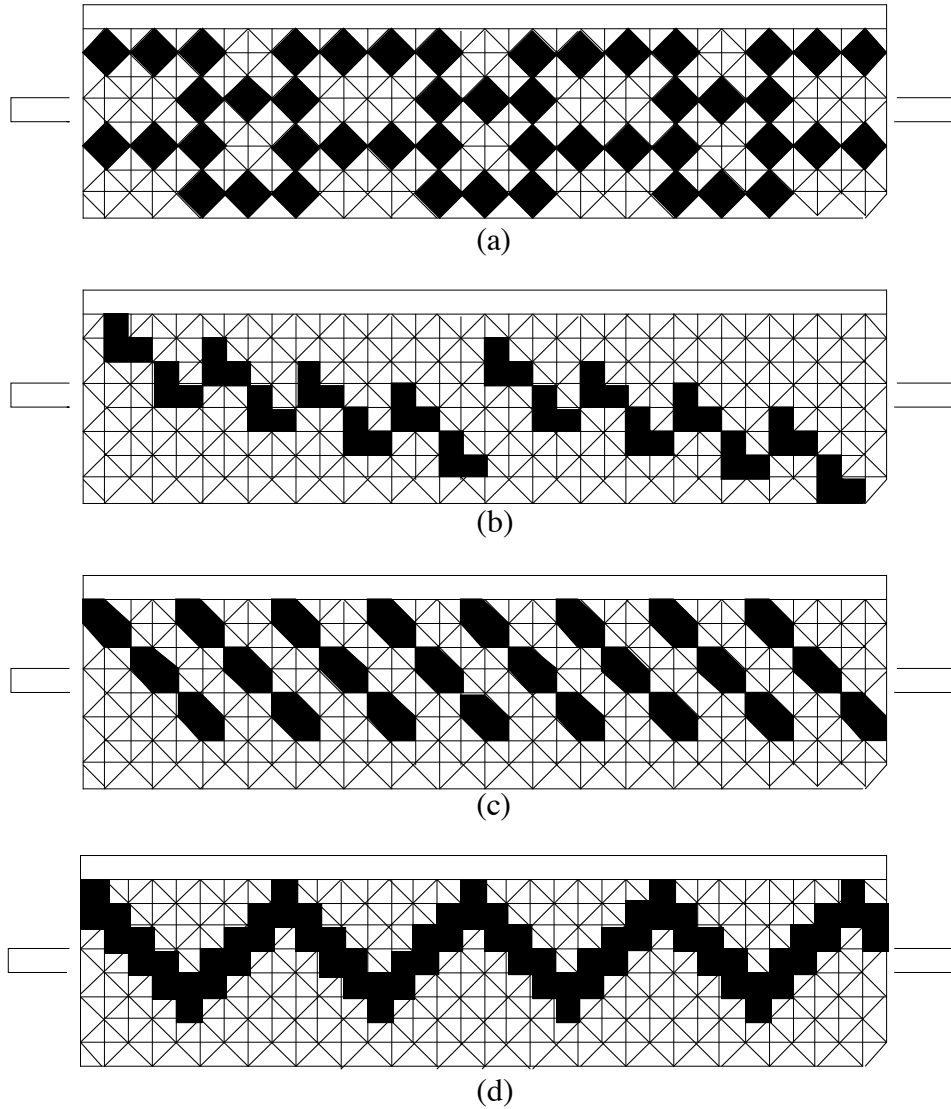
Figure 11: Examples of various types of visual rhythm as repeating groups of shapes

3.3 Process model

This computational model of shape semantics involves three processes as shown in Figure 12: (1) object correspondence: process 1; (2) grouping: process 2; and (3) shape semantics emergence: process 3. Given alternate representations, new interpretations become possible (Gero, et al 1995). Interpretation is the process of inferring results from a primary shape in a particular representation. Whenever the representation is changed, it may be possible to find some emergent properties from that representation. In this process the notion of infinite maximal lines is used as primitives of representation and emergent structures are found from that representation. Explicit structures are structures that exist explicitly in primary shapes. Emergent structures are structures that exist only implicitly

in primary shapes, and are never explicitly input and are not represented at input time. Corresponding infinite maximal lines and intersections are found through the process of object correspondence. Infinite maximal lines and intersections of infinite maximal lines are considered as structures of objects. Corresponding structures of objects are inferred by constraints on structures of objects resulting from behaviours of infinite maximal lines. After searching corresponding infinite maximal lines and intersections, corresponding intersections are grouped by the grouping process. If groups satisfy constraints on various types of shape semantics, then these shape semantics are emerged in the process of shape semantics emergence.
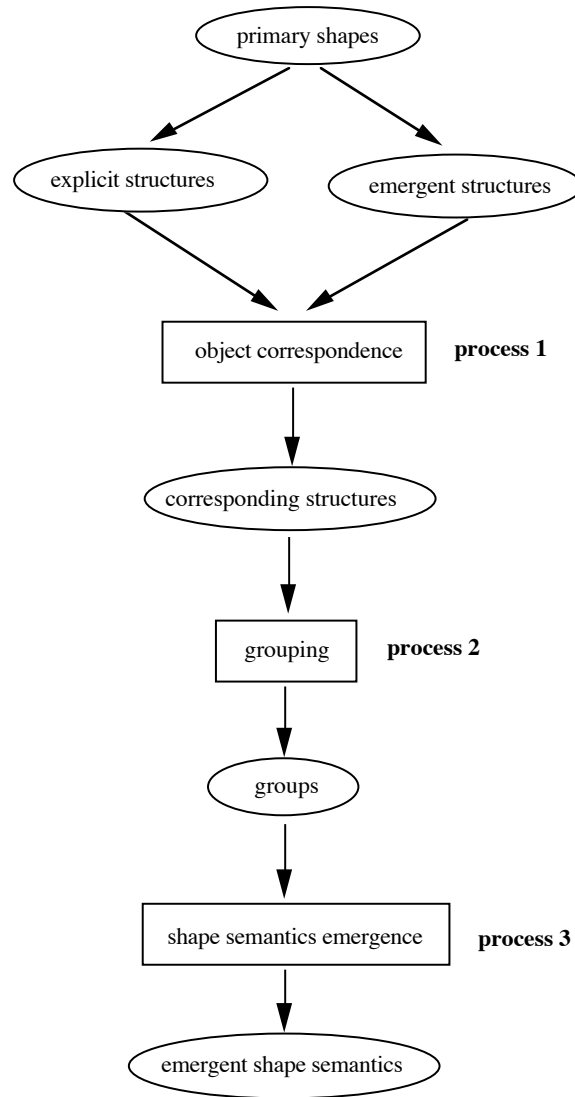
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                    ┌─────────────────┐
                    │  primary shapes │
                    └─────────────────┘
                      ↙             ↘
          ┌────────────────┐   ┌────────────────┐
          │explicit structures│ │emergent structures│
          └────────────────┘   └────────────────┘
                      ↘             ↙
                ┌──────────────────────┐
                │ object correspondence│   process 1
                └──────────────────────┘
                            ↓
                ┌──────────────────────┐
                │ corresponding structures│
                └──────────────────────┘
                            ↓
                     ┌──────────┐
                     │ grouping │   process 2
                     └──────────┘
                            ↓
                      ┌────────┐
                      │ groups │
                      └────────┘
                            ↓
                ┌──────────────────────┐
                │shape semantics emergence│   process 3
                └──────────────────────┘
                            ↓
                ┌──────────────────────┐
                │emergent shape semantics│
                └──────────────────────┘
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Figure 12: A computational process model of shape semantics emergence

3.3.1 Object correspondence

Object correspondence confirms that structures of one object are equivalent to structures of another object in terms of topology and geometry. As a consequence, corresponding

infinite maximal lines and intersections are found. There are three main steps for examining corresponding structures in explicit structures and emergent and explicit structures:

(I) finding corresponding structures in explicit structures - explicit structure correspondence, denoted **P1**;

(ii) finding corresponding structures in emergent and explicit structures - emergent structure correspondence, denoted **P2**; and

(iii) finding corresponding structures in emergent shapes or emergent shapes and primary shapes - emergent shapes correspondence, denoted **P3,** as shown in Figure 13.

Given two shapes, congruent corresponding structures are found when the number of infinite maximal lines, the number of intersections, geometrical properties of infinite maximal lines and dimensional constraints on segments in each infinite maximal line are equivalent. Explicit structure correspondence is the process of examining corresponding structures in explicit structures. In order to determine explicit structure correspondence, the number of infinite maximal lines and number of intersections in primary shapes, are checked first. After that, geometrical constraints on infinite maximal lines, such as parallelarity, perpendicularity, skewness and coincidence, are compared between two shapes. If those conditions are equivalent, explicit structure correspondence is satisfied.
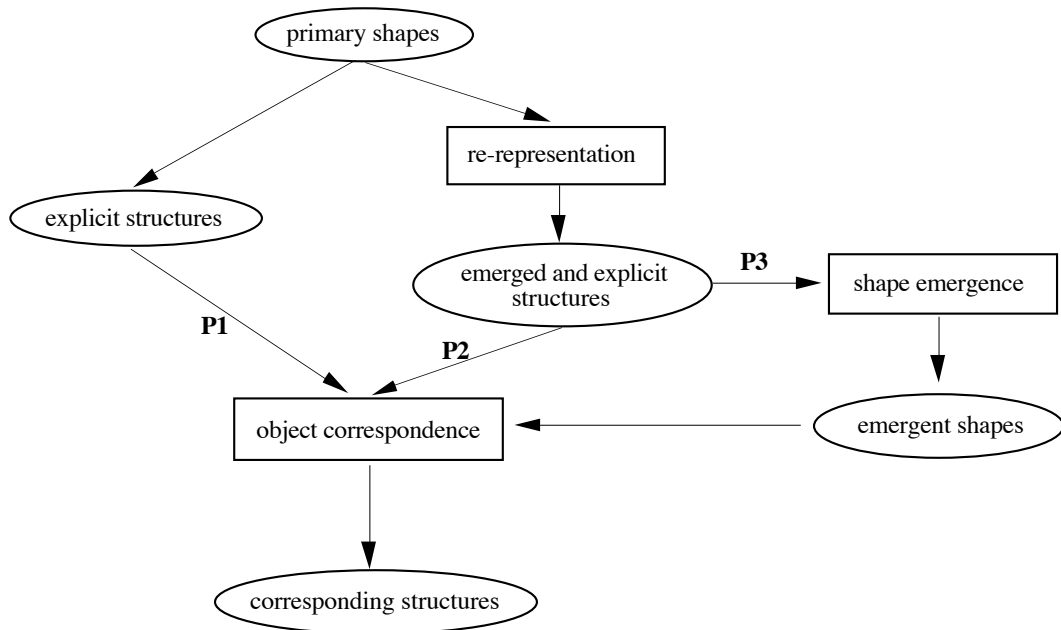

Figure 13: A process of object correspondence: **P1**- explicit structure correspondence; **P2**- emergent structure correspondence; and **P3**- emergent shapes correspondence.

After explicit structure correspondence is determined, the enclosed intersection group is destroyed or relaxed into an ordinary intersection group through re-representation (Gero and Yan, 1994). If explicit structure correspondence is satisfied, then corresponding structures in emergent and explicit structures in two shapes are examined through emergent structure correspondence. Corresponding infinite maximal lines are inferred. Corresponding intersections are inferred resulting from corresponding infinite maximal lines. Inference rules are introduced in the next section.

When explicit structure correspondence is not satisfied two primary shapes do not correspond. However, there is the possibility for corresponding shapes to exist between explicit and emergent structures. For example, given two primary shapes as shown in Figure 14(a), the number of infinite maximal lines are different. As a result, corresponding structures do not exist in these two primary shapes. Therefore, explicit structure correspondence is not satisfied.
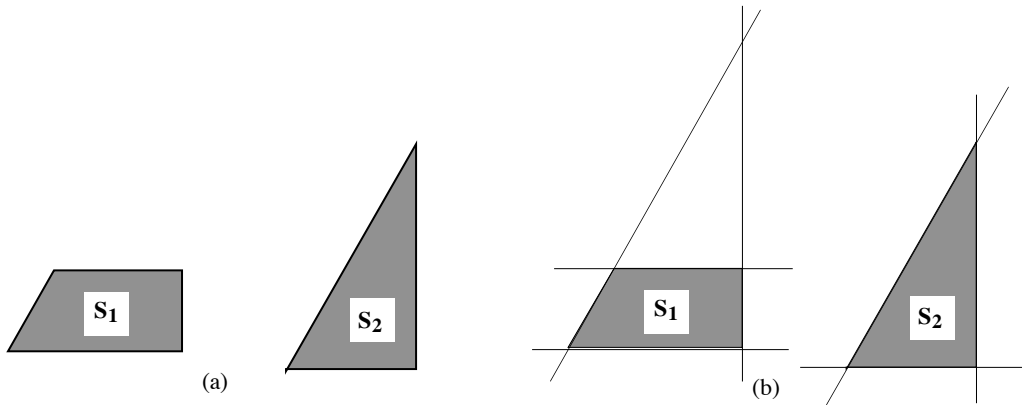

Figure 14: (a) Two primary shapes and (b) infinite maximal line representation of two primary shapes.

Through infinite maximal line representation, the enclosed intersection group is destroyed or relaxed into an ordinary intersection group as shown in Figure 14(b). As a consequence, emergent shapes from a primary shape S_1, S_{1-1} and S_{1-2}, are found and correspondence between emergent shapes and primary shapes is examined as shown in Figure 15.
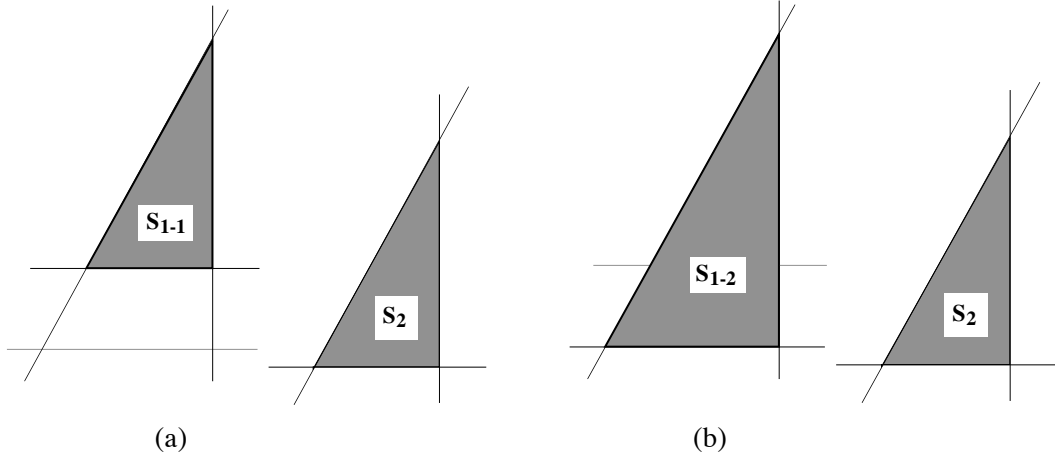
Figure 15: Correspondence between emergent shapes, S_{1-1} and S_{1-2}, and a primary shape, S_2.

If explicit structure correspondence is not satisfied, then emergent shapes are inferred through shape emergence (Gero and Yan, 1994) and corresponding structures between emergent shapes or emergent shapes and primary shapes are examined in the process of emergent shapes correspondence.

The number of intersections in each infinite maximal line, denoted as N_i, and the number of segments in each infinite maximal line, denoted as N_k, play major roles in finding corresponding infinite maximal lines. Corresponding infinite maximal lines in congruent objects are inferred by the following rule.

R1: $N_{i_a} = N_{i_p} \land N_{k_a} = N_{k_p} \land (\forall d(i_{ab}, i_{ac}) \in l_a = \forall d(i_{pq}, i_{pr}) \in l_p)$
$=> l_a \leftrightarrow l_p.$
Where N_{i_a} and N_{i_p} is number of intersections in l_a and l_p respectively and
N_{k_a} and N_{k_p} is number of segments in l_a and l_p respectively and
$\forall d(i_{ab}, i_{ac}) \in l_a$ means all dimensional constraints in l_a.

Finally, corresponding intersections are inferred by applying the following rule.

R2: $l_i \leftrightarrow l_p \land l_j \leftrightarrow l_q \land l_i \times l_j \land l_p \times l_q => i_{ij} \leftrightarrow i_{pq}.$

3.3.2. Grouping
Grouping is the process of searching various types of groups of line segments, enclosed shapes and groups of enclosed shapes resulting from grouping corresponding intersections (Gero and Yan, 1994). Grouping adjacent intersections may form enclosed shapes otherwise only line segment or groups of line segments are formed. There are two types of groupings:

(i) line segments grouping and
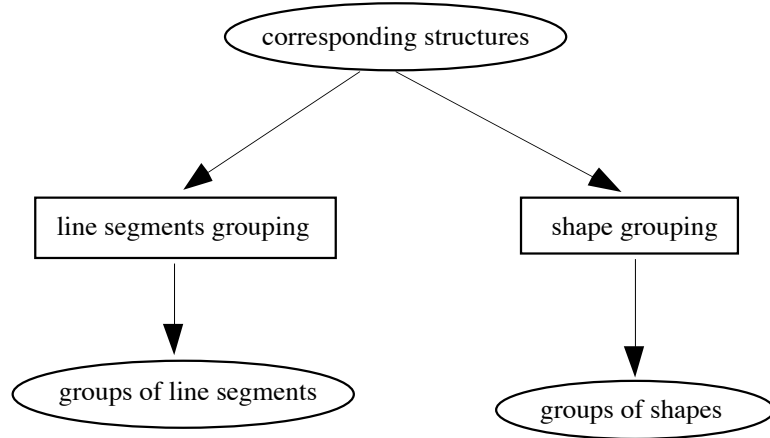
(ii) shape grouping as shown in Figure 16.

Figure 16: Process of grouping

Line segments grouping is grouping adjacent intersections which results in an ordinary group of intersections. For example, grouping i_{ab}, i_{ac}, i_{cd} does not form an enclosed shape but a group of line segments because there is no closure:

$$\mathbf{G} \ (i_{ab}, i_{ac}, i_{cd}) => L_g = \{3; (i_{ab}, i_{ac}, i_{cd})\}$$

where $\mathbf{G}$ denotes grouping operator and L_g denotes groups of line segments.

On the other hand, shape grouping is grouping adjacent intersections which results in an enclosed group of intersections. For example, grouping the intersections i_{ab}, i_{bd}, i_{ad} forms a triangle because l_a, l_b and l_d exist and intersect each other, ie:

$$\mathbf{G} \ (i_{ab}, i_{bd}, i_{ad}) => S = \{3; [i_{ab}, i_{bd}, i_{ad}]\}$$

Corresponding shapes and line segments are found through this process.

3.3.3. Shape semantics emergence

The process of shape semantics emergence is illustrated in Figure 17. Various types of symmetries are discovered by applying rules to congruent shape groups. These types of symmetries are also used when inferring different types of shape semantics. In particular, translational symmetry is used in the discovery of visual rhythm.
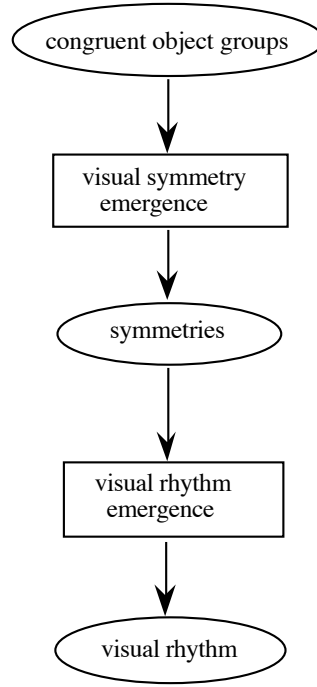
Figure 17: Process of shape semantics emergence

Different types of visual symmetries are discovered by applying rules to congruent groups, in which all structures are found by congruent object correspondence and are grouped. Let two congruent shapes be S_1 and S_2 and l_a, l_b, l_c, l_d belong to S_1 and l_p, l_q, l_r, l_s belong to S_2. The representation of two primary four-sided shapes is

$S_1 = \{4; [i_{ac}, i_{ad}, i_{bd}, i_{bc}]\}$
$S_2 = \{4; [i_{pr}, i_{ps}, i_{qs}, i_{qr}]\}.$

After shape hiding (Gero and Yan, 1994) emergent structures can be made explicit, so the representation of this example now becomes

$S_1 = \{4; (i_{bd}, i_{ab}, i_{bc}, i_{cd}, i_{ac}, i_{ad})\}$
$S_2 = \{4; (i_{qs}, i_{pq}, i_{pr}, i_{qr}, i_{rs}, i_{ps})\}.$

Let corresponding infinite maximal lines and intersections be:

$l_a \leftrightarrow l_p$, $l_b \leftrightarrow l_q$, $l_c \leftrightarrow l_r$, $l_d \leftrightarrow l_s$, and
$i_{ab} \leftrightarrow i_{pq}$, $i_{ac} \leftrightarrow i_{pr}$, $i_{ad} \leftrightarrow i_{ps}$, $i_{bc} \leftrightarrow i_{qr}$, $i_{bd} \leftrightarrow i_{qs}$, $i_{cd} \leftrightarrow i_{rs}$.

Following corresponding shapes are discovered by grouping some of corresponding intersections:

G_1 $(i_{ab}, i_{ac}, i_{bc}) => S_{1\text{-}1} = \{3; [i_{ab}, i_{ac}, i_{bc}]\}$

G_2 $(i_{pq}, i_{pr}, i_{qr}) => S_{2\text{-}1} = \{3; [i_{pq}, i_{pr}, i_{qr}]\}.$

The following constructed segments are implied by corresponding intersections.

$i_{ab} \leftrightarrow i_{pq} => \mathbf{c}(i_{ab}, i_{pq}),$

$i_{ac} \leftrightarrow i_{pr} => \mathbf{c}(i_{ac}, i_{pr}),$

$i_{bc} \leftrightarrow i_{qr} => \mathbf{c}(i_{bc}, i_{qr}).$

Symmetries are discovered if one of following rules is satisfied:

R3: $\mathbf{c}(i_{ab}, i_{pq}) \mathbin{/\!/} \mathbf{c}(i_{ac}, i_{pr}) \mathbin{/\!/} \mathbf{c}(i_{bc}, i_{qr}) \wedge l_a \mathbin{/\!/} l_p, \; l_b \mathbin{/\!/} l_q, \; l_c \mathbin{/\!/} l_r$

$=>$

$\mathbf{c}(i_{ab}, i_{pq}) \cup \mathbf{c}(i_{ac}, i_{pr}) => \{4 \,;\, [i_{ab}, i_{pq}, i_{ac}, i_{pr}] \,;\, l_a \mathbin{/\!/} l_p, \mathbf{c}(i_{ab}, i_{pq}) \mathbin{/\!/} \mathbf{c}(i_{ac}, i_{pr})\},$

$\mathbf{c}(i_{ab}, i_{pq}) \cup \mathbf{c}(i_{bc}, i_{qr}) => \{4 \,;\, [i_{ab}, i_{pq}, i_{bc}, i_{qr}] \,;\, l_b \mathbin{/\!/} l_q, \mathbf{c}(i_{ab}, i_{pq}) \mathbin{/\!/} \mathbf{c}(i_{bc}, i_{qr})\},$

$\mathbf{c}(i_{ac}, i_{pr}) \cup \mathbf{c}(i_{bc}, i_{qr}) => \{4 \,;\, [i_{ac}, i_{pr}, i_{bc}, i_{qr}] \,;\, l_c \mathbin{/\!/} l_r, \mathbf{c}(i_{ac}, i_{pr}) \mathbin{/\!/} \mathbf{c}(i_{bc}, i_{qr})\},$

$=> S_\tau$ (translational symmetry).

Translational symmetry is discovered when **R3** is satisfied as shown in Figure 18.
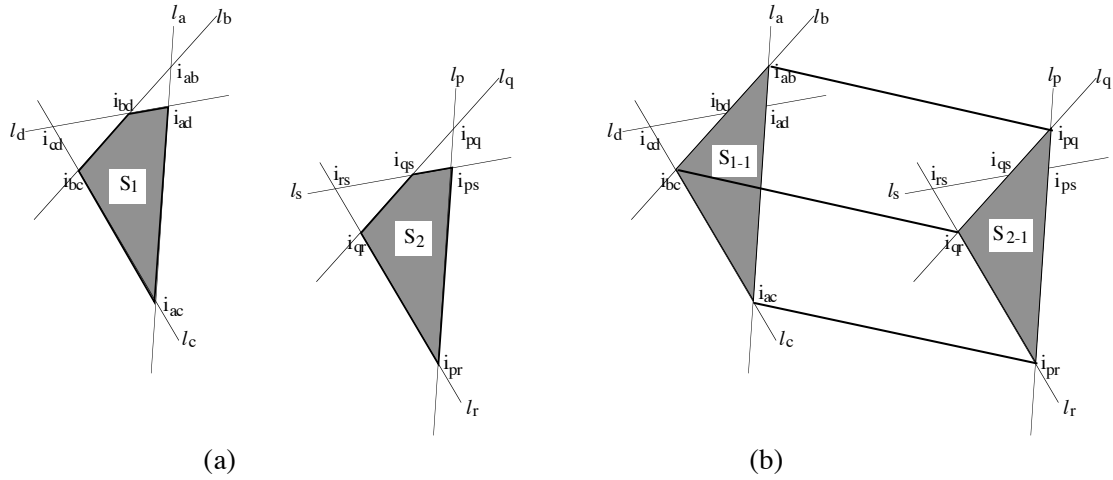

(a)   (b)

Figure 18: Translational symmetry is illustrated graphically: (a) two primary four sided shapes and (b) one translational symmetry from (a).

R4: $\mathbf{c}(i_{ab}, i_{pq}) \mathbin{/\!/} \mathbf{c}(i_{ac}, i_{pr}) \mathbin{/\!/} \mathbf{c}(i_{bc}, i_{qr})$

$=>$

$\mathbf{c}(i_{ab}, i_{pq}) \cup \mathbf{c}(i_{ac}, i_{pr}) => \{4 \,;\, [i_{ab}, i_{pq}, i_{ac}, i_{pr}] \,;\, \mathbf{c}(i_{ab}, i_{pq}) \mathbin{/\!/} \mathbf{c}(i_{ac}, i_{pr})\},$

$\mathbf{c}(i_{ab}, i_{pq}) \cup \mathbf{c}(i_{bc}, i_{qr}) => \{4 \,;\, [i_{ab}, i_{pq}, i_{bc}, i_{qr}] \,;\, \mathbf{c}(i_{ab}, i_{pq}) \mathbin{/\!/} \mathbf{c}(i_{bc}, i_{qr})\},$

$\mathbf{c}(i_{ac}, i_{pr}) \cup \mathbf{c}(i_{bc}, i_{qr}) => \{4 \,;\, [i_{ac}, i_{pr}, i_{bc}, i_{qr}] \,;\, \mathbf{c}(i_{ac}, i_{pr}) \mathbin{/\!/} \mathbf{c}(i_{bc}, i_{qr})\},$

$\wedge \; i_{\mathbf{c}(i_{ab}, i_{pq})\mathbf{M}}, \; i_{\mathbf{c}(i_{ac}, i_{pr})\mathbf{M}}, \text{ and } i_{\mathbf{c}(i_{bc}, i_{qr})\mathbf{M}} \text{ lie in a certain } l_m.$

$\wedge\ l_{\mathbf{M}_1} = l_{\mathbf{M}_2} = l_{\mathbf{M}_3},$

(Let $l_{\mathbf{M}}^{\mathbf{c}^{(i_{ab},\ i_{pq})}}$ be $l_{\mathbf{M}_1}$, $l_{\mathbf{c}}({}^{i_{ac},\ i_{pr}},\mathbf{M})$ be $l_{\mathbf{M}_2}$ and $l_{\mathbf{M}}^{\mathbf{c}^{(i_{bc},\ iqr)}}$ be $l_{\mathbf{M}_3}$)

$\Rightarrow S_\rho$ (reflectional symmetry).

$\quad$ (L (reflectional axis) $= l_{\mathbf{M}_1} = l_{\mathbf{M}_2} = l_{\mathbf{M}_3}$).

Reflectional symmetry is discovered when **R4** is satisfied as shown in Figure 19.
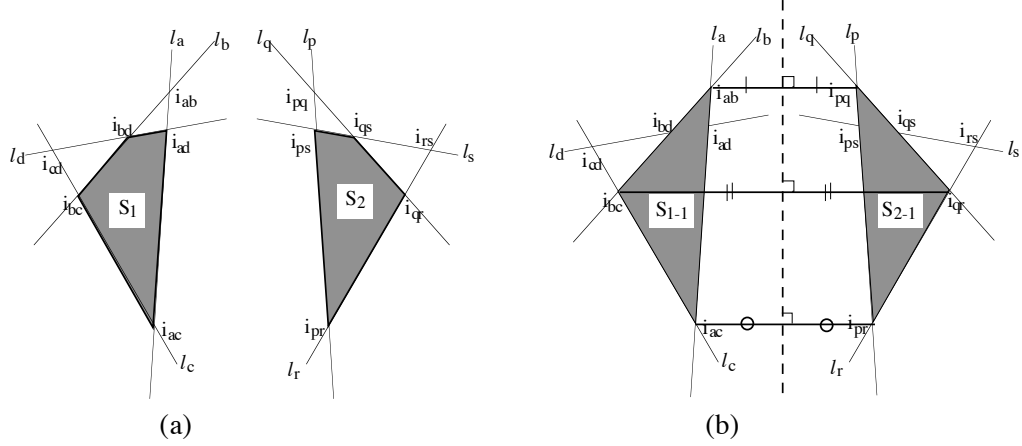

(a) $\qquad\qquad\qquad\qquad$ (b)

Figure 19: Reflectional symmetry is illustrated graphically: (a) two primary four sided shapes and (b) one reflectional symmetry from (a).

R5: $\exists\ i_{\mathbf{M}_1\mathbf{M}_2\mathbf{M}_3}$,

(Let $l_{\mathbf{M}}^{\mathbf{c}^{(i_{ab},\ i_{pq})}}$ be $l_{\mathbf{M}_1}$, $l_{\mathbf{c}}({}^{i_{ac},\ i_{pr}},\mathbf{M})$ be $l_{\mathbf{M}_2}$ and $l_{\mathbf{M}}^{\mathbf{c}^{(i_{bc},\ iqr)}}$ be $l_{\mathbf{M}_3}$)

$\Rightarrow S_\sigma$ (rotational symmetry).

$\quad$ (rotational point is $i_{\mathbf{M}_1\mathbf{M}_2\mathbf{M}_3}$).

Rotational symmetry is discovered when **R5** is satisfied as shown in Figure 20.

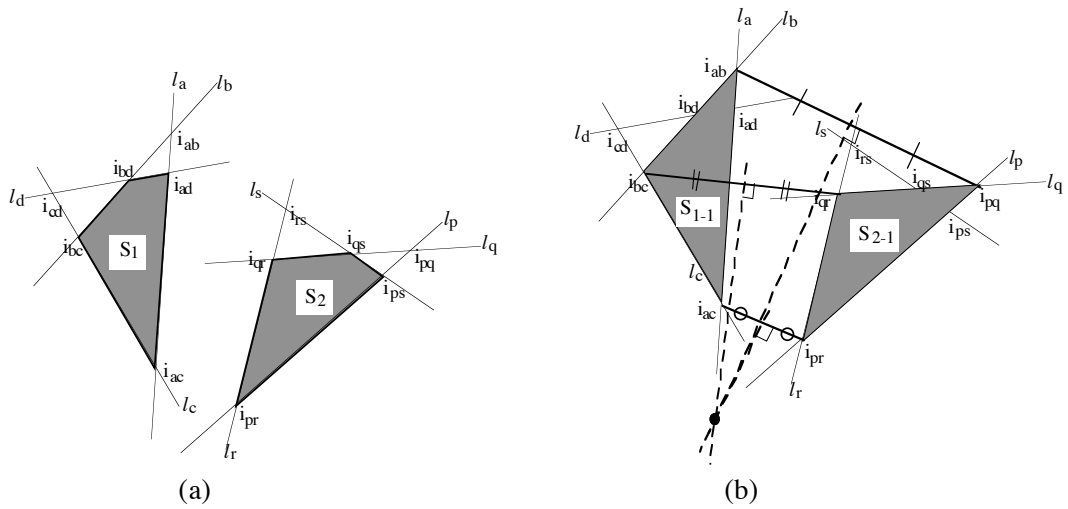(a) $\qquad\qquad\qquad\qquad$ (b)

Figure 20: Rotational symmetry is illustrated graphically: (a) two primary four sided shapes and (b) one rotational symmetry from (a).

R6: $i_{\mathbf{c}}(i_{ab}, i_{pq})\mathbf{M}$, $i_{\mathbf{c}}(i_{iac}, i_{pr})\mathbf{M}$, and $i_{\mathbf{c}}(i_{bc}, iqr)\mathbf{M}$ lie in a certain l_m

$\wedge$ NOT $l_{\mathbf{M}_1} = l_{\mathbf{M}_2} = l_{\mathbf{M}_3}$,

(Let $l_{\mathbf{M}}^{\mathbf{c}^{(i_{ab},\, i_{pq})}}$ be $l_{\mathbf{M}_1}$, $l_{\mathbf{c}}^{(i_{iac},\, i_{pr})}$,$\mathbf{M}$) be $l_{\mathbf{M}_2}$ and $l_{\mathbf{M}}^{\mathbf{c}^{(i_{bc},\, iqr)}}$ be $l_{\mathbf{M}_3}$)

$\Rightarrow S_\gamma$ (glide reflectional symmetry).

Glide reflectional symmetry is discovered when **R6** is satisfied as shown in Figure 21.

Visual rhythms are discovered as repetitions of congruent object groups. They are found when equivalent translational constraints exist over congruent object groups. A visual rhythm is discovered when the following rule is satisfied.

R7: $\tau_i(G_i) = G_{i+1}$, $\tau_{i+1}(G_{i+1}) = G_{i+2}$, ...

$\wedge$ $\tau_i = \tau_{i+1} = \tau_{i+2} = $ ......

$\Rightarrow \exists R$

(where G_i, G_{i+1}, G_{i+2}, ... are congruent object groups).

Figure 22 shows two different types of visual rhythms for i=1, ..., 5 having different constraints: Figure 22(a) has → constraint and Figure 22(b) has ↗ constraint. The congruent object group in Figure 22 is ◣.

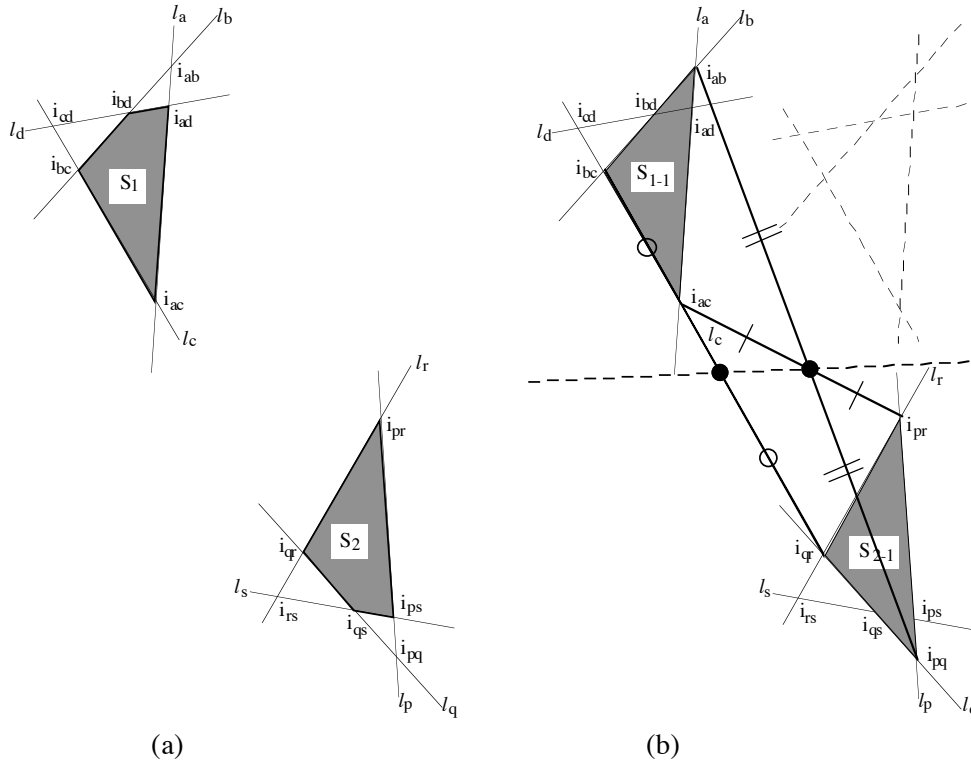(a)   (b)

Figure 21: Glide reflectional symmetry is illustrated graphically: (a) two primary four sided shapes and (b) one glide reflectional symmetry from (a).
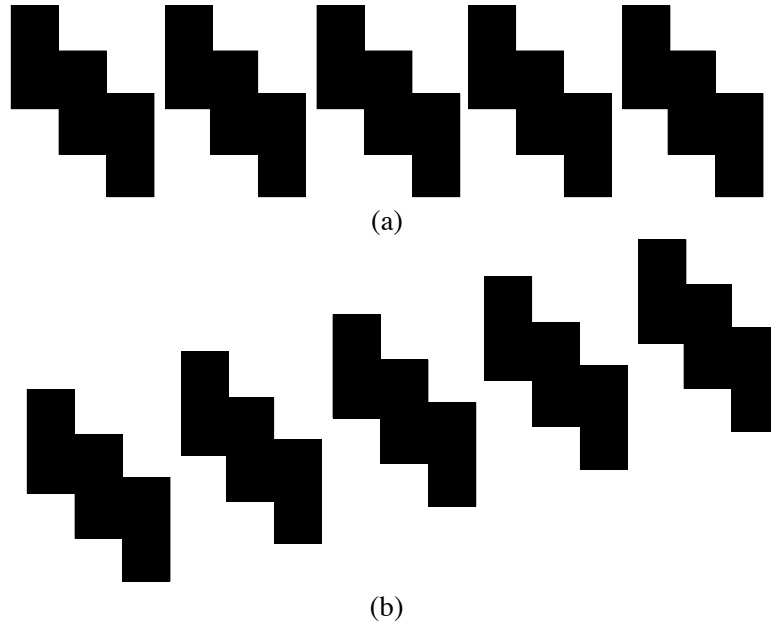
(a)

(b)

Figure 22: Two different types of visual rhythm are illustrated with the same congruent object groups.

3.4 Self symmetry

Self symmetries are symmetries discovered within an individual shape.

Features of self symmetry

1. If a self symmetry is reflectional symmetry, then the axis of symmetry passes through the centre of gravity.

2. If a self symmetry is rotational symmetry, then the centre of symmetry is congruent with the centre of gravity.

3. If a self symmetry is translational symmetry, translated parts in a shape are distinguished by an axis passing through the centre of gravity.

Let l_g be an infinite maximal line passing through a centre of gravity denoted, as i_g. There is an infinite number of l_gs. On the other hand, l_G is the infinite maximal line passing through a centre of gravity and satisfying certain conditions of interest here. We call l_G the self symmetry axis. There are three kinds of l_Gs.

l_G exists when the following rules are satisfied:

1. l_G passes through a centre of gravity and midpoints of segments, as shown in Figure 23.

Midpoints of two segments, $i_{(i_{ik}, i_{kp})M}$ and $i_{(i_{ip}, i_{pq})M}$, and i_g are collinear $\Rightarrow \exists \, l_G$.
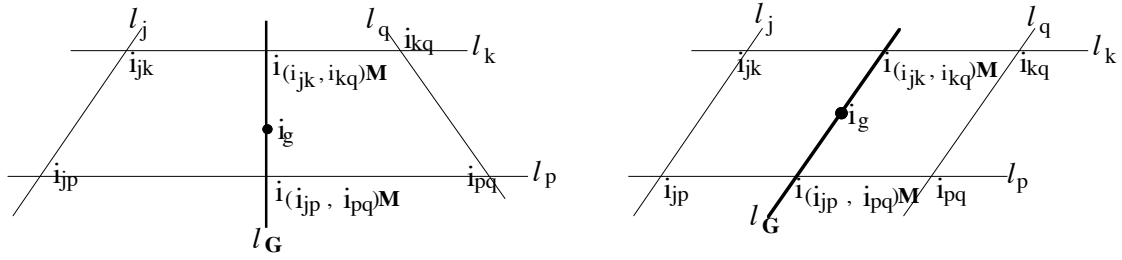
Figure 23: Inferring l_G from a centre of gravity and midpoints of segments.

2. l_G passes through a centre of gravity and intersections, as shown in Figure 24.

Two intersections, i_{jk} and i_{pq}, and i_g are collinear $\Rightarrow \exists\, l_G$.
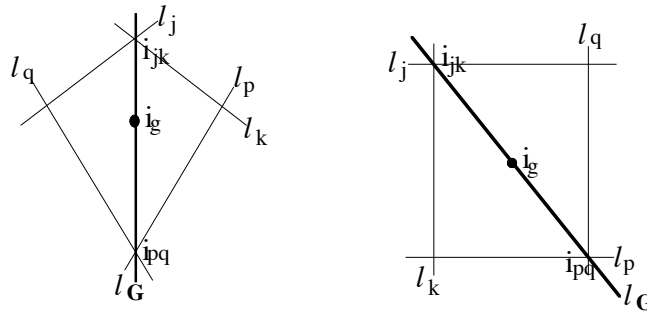

Figure 24: Inferring l_G from a centre of gravity and intersections.

3. l_G passes through a centre of gravity and one midpoint of a segment and one intersection, as shown in Figure 25.

Midpoints of one segment in each shape, $i_{(i_{ik},\, i_{ik})M}$ and $i_{(i_{pk},\, i_{qk})M}$, one intersection in each shape, i_{ij}, and i_g are collinear $\Rightarrow \exists\, l_G$.
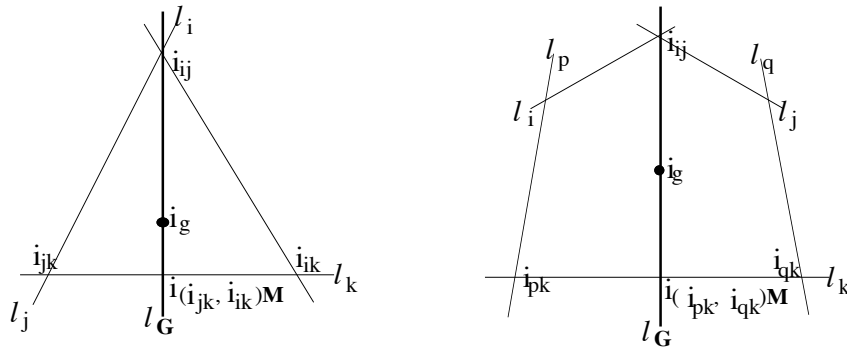

Figure 25: Inferring l_G from a centre of gravity and one midpoint of a segment and one intersection.

If l_G exists, then divide given primary shape into two shapes about l_G. Through the process of object correspondence and visual symmetry emergence various self symmetries are discovered.

4 Architectural example

The architectural plan for the Bio-2 Complex in the Headquarters for Bayer AG designed by James Stirling, Michael Wilford and Associates is analysed to discover various types of symmetries. The Bio-2 Complex building is one of various laboratory complexes in the headquarters for Bayer AG. The overhead view and plan of the Bio-2 Complex are shown in Figures 26(a) and (b). Through the process of visual symmetry emergence, all possible symmetries are discovered from this example. Among them, some of symmetries are shown in Figures 26(c), (d) and (e). Choosing only some symmetries to work with depends on the designer's interest. Figure 26(c) shows self reflectional symmetry is discovered by the process of self symmetry axis inference. In addition to self symmetry, some parts of this plan have reflectional symmetry about the same axis of self symmetry as shown in Figure 26(d). Rotational symmetry is discovered as shown in Figure 26(e). Four sided polygons in this plan are rotated at the centre of rotation. The centre of rotation is inferred by the rotational constraints.

The symbolic representation of the shape in Figure 27 is

$S = \{39; [i_{5\mathit{15}}, i_{10\mathit{15}}, i_{10\mathit{16}}, i_{11\mathit{15}}, i_{11\mathit{16}}, i_{12\mathit{17}}, i_{12\mathit{16}}, i_{14\mathit{16}}, i_{14\mathit{21}}, i_{12\mathit{21}}, i_{12\mathit{20}}, i_{11\mathit{20}}, i_{11\mathit{26}}, i_{826},$
$i_{827}, i_{927}, i_{9\mathit{30}}, i_{13\mathit{30}}, i_{13\mathit{31}}, i_{18\mathit{31}}, i_{18\mathit{32}}, i_{32\mathit{37}}, i_{36\mathit{37}}, i_{18\mathit{36}}, i_{18\mathit{35}}, i_{13\mathit{35}}, i_{13\mathit{34}}, i_{9\mathit{34}}, i_{9\mathit{33}}, i_{29\mathit{33}},$
$i_{629}, i_{628}, i_{228}, i_{223}, i_{23\mathit{38}}, i_{28\mathit{38}}, i_{23\mathit{39}}, i_{19\mathit{39}}, i_{19\mathit{38}}, i_{22\mathit{38}}, i_{222}, i_{224}, i_{224}, i_{627}, i_{727}, i_{726}, i_{426},$
$i_{420}, i_{3\mathit{20}}, i_{3\mathit{21}}, i_{12\mathit{1}}, i_{11\mathit{16}}, i_{3\mathit{16}}, i_{3\mathit{17}}, i_{4\mathit{17}}, i_{4\mathit{16}}, i_{5\mathit{16}}], l_1 \mathbin{/\!/} l_3 \mathbin{/\!/} l_4 \mathbin{/\!/} l_5 \mathbin{/\!/} l_7 \mathbin{/\!/} l_8 \mathbin{/\!/} l_{10} \mathbin{/\!/} l_{11} \mathbin{/\!/} l_{12}$
$\mathbin{/\!/} l_{14}, \; l_{15} \mathbin{/\!/} l_{16} \mathbin{/\!/} l_{17} \mathbin{/\!/} l_{20} \mathbin{/\!/} l_{21} \mathbin{/\!/} l_{26} \mathbin{/\!/} l_{27}, \; l_1 \perp l_{15}\}.$

This representation is based on walls between the inner and outer spaces in the plan.

Various types of symmetries are discovered from the primary shape representation in Figure 28. After the self symmetry axis, l_G, is inferred, the primary shape is divided into two shapes, S_1 and S_2 as shown in Figure 28(a). Correspondence between these two shapes is inferred. As a consequence, self reflectional symmetry is discovered by satisfying **R4**. Furthermore, all possible types of symmetry are discovered using the rules in Section 3.3.3, Figure 26(d). However, we deal with only some of types of symmetries as shown in Figure 28(b). Translational symmetry and reflectional symmetry are discovered from two shapes, S_3 and S_4. Three different individual reflectional symmetries are discovered from S_5 and S_6, S_6 and S_7 and S_7 and S_8. A

group of corresponding shapes is recognized as having reflectional symmetry: $\tau[G(S_3,$
$S_5, S_6)] = G(S_4, S_8, S_7)$. Finally rotational symmetry from four congruent shapes, S_5,
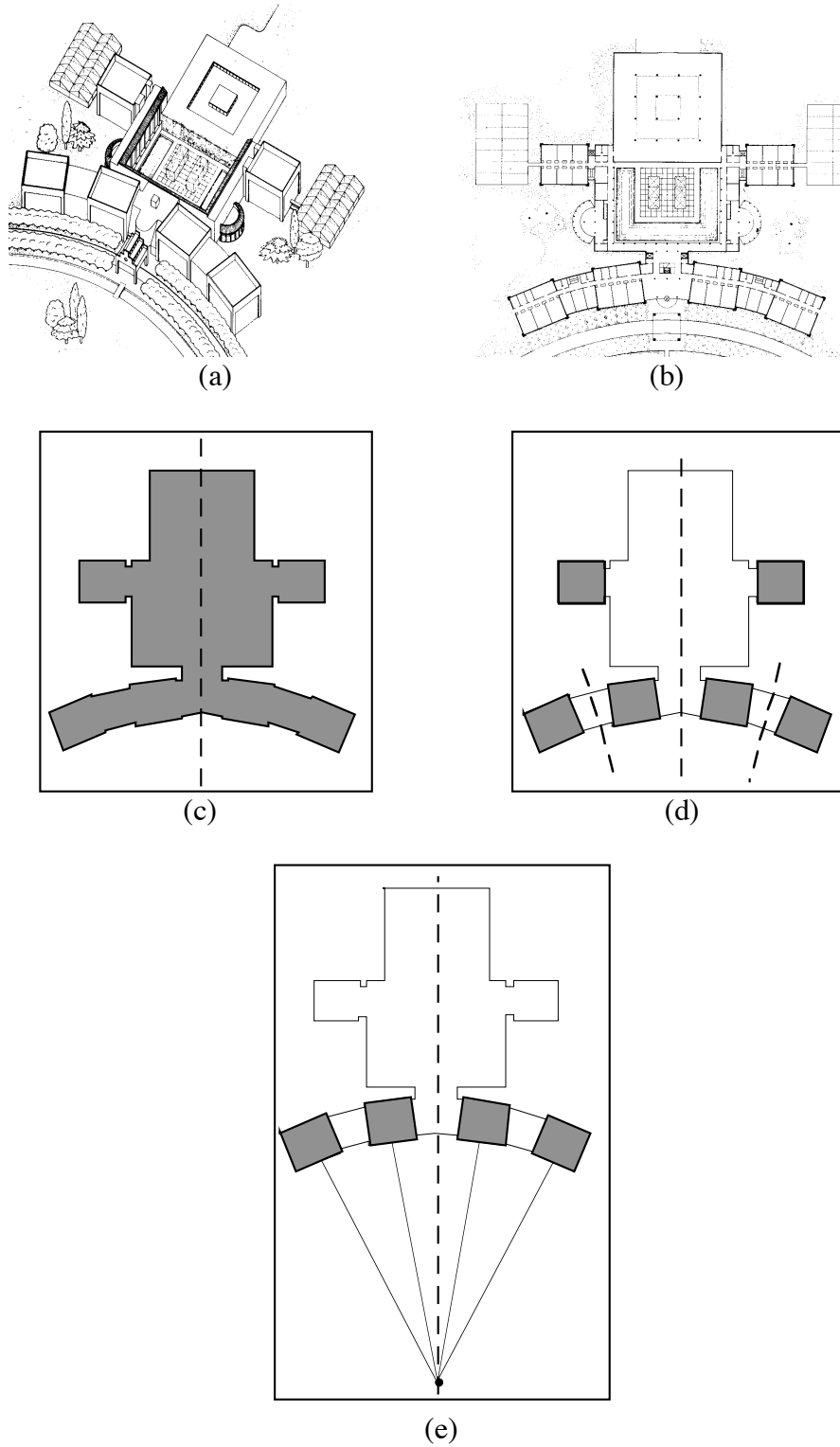S_6, S_7 and S_8, is discovered.

Figure 26: The Bio-2 Complex in the Headquarters for Bayer AG (James Stirling, Michael Wilford and Associates, 1978); (a) overhead view of the complex, (b) plan of

the complex, (c) self reflectional symmetry, (d) reflectional symmetry and (e) rotational symmetry.
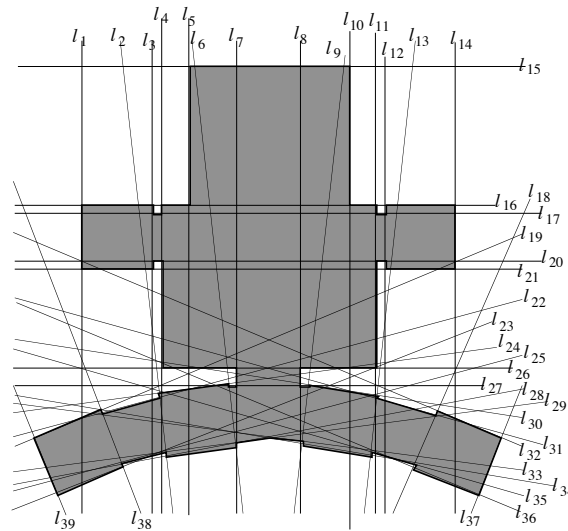

Figure 27: Primary shape representation of Figure 26(b)

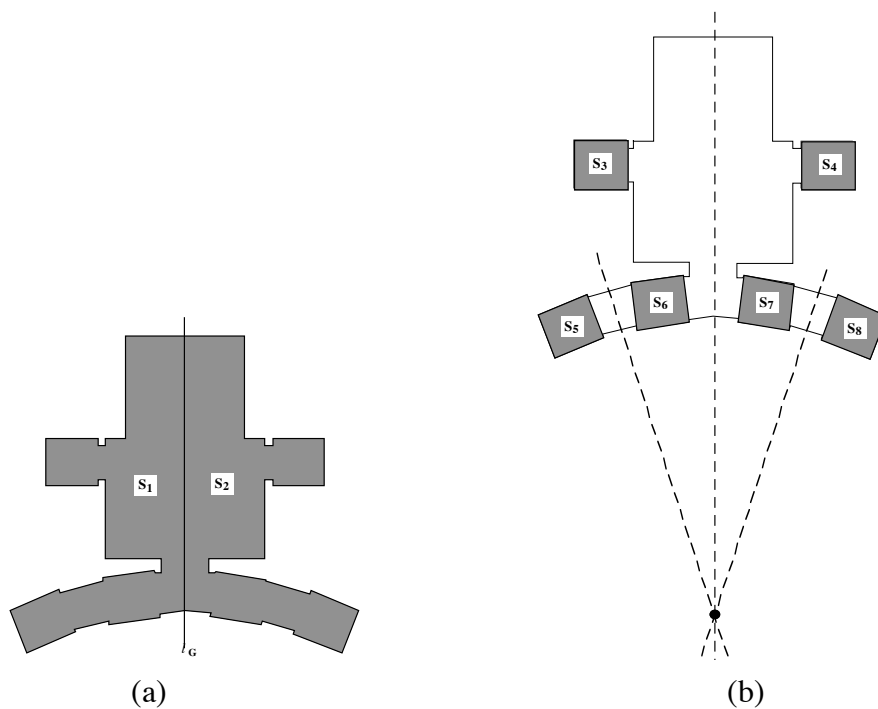(a)   (b)

Figure 28: Symmetries are emerged: (a) self reflectional symmetry of Figure 26(c) and (b) some of reflectional symmetries and rotational symmetry of Figures 26(d) and (e)

In a similar fashion all other semantics could be emerged if they can be found to exist in this representation of the drawing.

5 Conclusion

Shape semantics play an important role in organising decisions, providing order, and generating final form in visually-oriented design. They appear to have a special role in architectural design in particular. Architecture reflects its main design concept through

visual organization of structures. Such organization is seen as the visual semantics of the design and is perceivable to designers. However, current computer-aided drawing, computer-aided drafting and computer-aided design systems prevent the discovery of visual shape semantics. Inadvertently such systems have enforced fixation so that it is not surprising that they are not used in the early stages of architectural design. The fixation they enforce has two sources: the system designer and the way the architect has described his or her drwaing. The CAAD system's designer's views on what is permissible creates an unstated and sometimes unkown set of limitations on the use of the system.

The ability to discover visual semantics from shapes readily offer opportunities to develop design-oriented graphics system which may be more amenable to augment designers abilities during the early conceptual stage of design. We have developed symbolic representations of shape semantics, visual symmetry and visual rhythm, for two dimensional shapes using infinite maximal lines as its basis. This representation has been used as the basis of an implementation to support early stages of design in visually-oriented design fields particularly in architectural design.

We can conceive of a variety of other visual semantics from architectural shapes such as visual movement and visual balance. These shape semantics can be symbolically represented at different levels of abstraction, where the symbolic representation can be characterised to allow it to be mapped onto various hypotheses.

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