

Towards a Computational Analysis of Style in Architectural Design

Content Areas: Two-dimensional drawings, qualitative representation, information theory.

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Abstract

Architectural plans are drawings that describe building layout where spatial planning is designed according to design requirements in the style of the designer. Style in architecture is generally characterised as common features appearing in a particular class of building designs. The question is: How do we recognize the style of architectural designs? We explore this question in a computational Encoder-Analyser (E-A) model for building plans, where a characterisation of two-dimensional architectural style is based on qualitative representation and information theoretic measures. In a preliminary study of a prominent architect's plans we demonstrate the effectiveness of our approach. We conclude by discussing practical applications of automated plan classification in design support tools.

Introduction

Research in various domains share problems of formalizing style. The architectural design domain is no exception and in most cases a designer's style is difficult to determine formally. In all visual domains, style is commonly used to describe consistencies among artefacts that are the product of an individual, culture, period, or region. In this way, style in architectural design acts as an ordering principle, allowing building designs to be structured and providing order within an otherwise apparently chaotic domain [Knight, 1994].

The style of a building can be based on different representations and evaluated using a number of attributes. Here, two principal aspects concern us: firstly, visual representation, which can be two- (2D) or three-dimensional (3D); and secondly: building physicality, which encompasses many systems. Our approach to building physicality distinguishes two criteria: form elements and relationships, considered by Shapiro, [1961] as being significant to a characterisation of style. From this regard, shape, solid, void, mass as well as their spatial relationships can be recognised visually from 2D or 3D contours. We have chosen to focus our attention on 2D representation and use architectural plan drawings as our analytical vehicle. Plan drawings are a primary mode of building design representation. The plan is valuable in a characterisation of

architectural style as it is a standard mode of design representation. Before buildings are constructed allocation of spaces are typically represented in a set of technical plans; and prior to the technical stage conceptual sketches are commonly used to facilitate problem solving during designing. Thus, whilst acknowledging alternative approaches to architectural style we limit our scope to 2D representations.

2D representation is important in understanding how architectural style works in drawing and how we compare architectural plan design. Specifically, we ask how can we formally distinguish between plans; judge them as similar; and importantly recognise a designer's style?

In this paper we present an Encoding-Analysis (E-A) model capable of identifying and comparing 2D plans using stylistic discriminators. We define stylistic discriminators as design features which remain approximately invariant within a drawing of a given designer but which tend to vary from designer to designer. We show that 2D plans contain important local and global features that are important in discriminating between designs.

The remainder of this paper is divided into six sections. A survey of related work is carried out in Section 2. Qualitative representation of 2D plans and the information theoretic tools used in measurement are described in Section 3. These concepts are demonstrated in a study on Frank Lloyd Wright's residential building plans and the results are presented in Section 4. Section 5 discusses various issues of this approach and Section 6 concludes the paper.

2. Background

In order to address how a computational model of style in architectural design will operate we must first ask the following:

- How to perceive and recognise a 2D plan drawing for a variety shape and spatial features?
- What kind of shape and spatial representation will adequately characterise drawing style, and relate to design semantics?
- What kind of measure will enable comparison of design features and span concepts of complexity and similarity?

2.1 Approach to Perception

Objects such as architectural plans carry with them a great deal of information and our visual and spatial reasoning skills are essential in developing an understanding of them. From the viewer's perspective, a 2D plan is immediately understandable or not, based on the ease by which it can be processed. Processing 2D images depends on both shape elements and relationships [Klinger and Salingaros, 2000].

Automating 2D plan recognition is a complex problem, since geometrical elements used to describe shapes in a plan drawing transform due to different relationships created by a shape's connections with other shapes. For example, in Figure 1 the geometry of Shape A remains constant and is made up of four right angles, yet corresponding elements that previously defined the object are transformed by the addition of another shape. Figure 1 illustrates possible combinations of connectivity for Shape A.

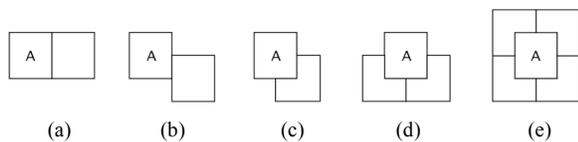


Figure 1. Types of shape relations: (a) meets, met-by, (b) offset (c), (d) and (e) contains, contained-by.

Shape A in Figure 1 maintains the same morphological description of four adjacent right-angles. However when shape A is combined with one, two, or more other shapes (in a finite number of ways) it produces: (a) a new description at its intersections and/or (b) additional intersections. The shape's physicality may be explicit and yet misleading, because a description of it may not correspond to the arrangements embedded in its contours.

Different levels of processing are therefore required for perceiving and recognising 2D plans, creating the need to take sensory data as input and produce higher-level information. This is reminiscent of the computational theory of vision proposed by Marr [1982]. In Marr's theory, vision is a process that produces a series of internal descriptions at increasing levels of abstraction. Marr's three stages in vision proceed from the input image to produce: a Primal Sketch where the "Raw Primal Sketch" represents edges and the "Full Primal Sketch" represents groupings of edges (on the basis of Gestalt principles such as classes, etc.); the Primal Sketch then leads to the production of a 2.5D Sketch, representing higher-level features (surfaces and orientation); and finally a 3D Model, is produced representing more abstract features and relations. Marr's theory relates to the problem we are addressing in that recognition and association are ultimately achieved with abstract features of relations that represent meaningful properties of the external world.

In order to recognize architectural plans, information must be captured and described at a variety of levels, abstracting away from the original representation and characterizing information, rather than exactly replicate the shapes as well as the spatial relations perceived. This raises

the question: how can we abstract and represent different levels of 2D plan information computationally so that the description contains the knowledge required to recognise a variety of higher-level information for design analysis and reasoning tasks. We explore one approach based on qualitative representation and reasoning.

2.2 Approach to Representation

Many solutions to the problem of representation in 2D diagrams have been proposed using a variety of data structures. The choice of data structure and applications to represent the 2D plan are crucial to the type of analysis tasks required. Representation can be divided into a number of different approaches: quantitative versus qualitative; grammar-like and non-grammar-like formalisms; and region-based or boundary-based.

There are substantial differences between these approaches and formalisms in regard to both framework and basic building blocks. However, schemas of the boundary-based approach use descriptors which are ultimately analysable in terms of qualitative variation. The benefits of using QFB representations lie in their ability to lend themselves to semantic interpretation, which have meaningful labels for designers. Qualitative feature-based (QFB) approaches have broadly been used in geometric assessment [Meeran and Pratt, 1993; Brown et al., 1995; Tombre, 1995]. We focus on QFB specification to explore a multi-level representation of 2D information.

In design reasoning, QFB representation has not been as extensively studied. Gero and Park [1997] developed a schema founded on Freeman's chain coding scheme [1961] using landmark-based qualitative codes. Until recently, the approach to boundary landmarks was restricted to representing the outline or silhouette of shapes in isolation. A schema that extended landmark descriptions to include spatial information was developed by Gero and Jupp [2003]. This approach produces classes of spatial features and enables design knowledge related to the qualitative character of the plan topology to be captured. We utilise this approach in a schema that defines a three-class qualitative language hierarchy for shape and space and derive canonical representation at each level.

2.3 Approach to Analysis and Reasoning

Once a 2D object is represented canonically, its features can be compared to obtain a measure of their "likeness". The notion of "likeness" can be highly subjective, since it depends on the criteria chosen and therefore contextual knowledge is required. Despite this requirement, there have been various solutions proposed for automated image processing and comparative analysis [Atneave, 1966; Pavlidis, 1977; Watanabe et al, 1995; Do and Gross, 1995; Park and Gero, 2000; Gero and Kazakov, 2001; Colagrossi, et al, 2003]. Form recognition studies have also based processing systems on summarising line intersection information in 1D strings [Ting et al, 1995; Lin et al, 1996].

Comparative analysis can generally be divided into statistical measures or machine learning methods. In the arts

and linguistics methods used to recognise and classify have predominantly been based on statistical methods where information theoretic tools have dominated. Generally the objective of such studies is to provide access to data measurement in order to derive digital characterisations where variety, diversity and differentiation are the target of generalisations.

We implement information theoretic tools as a principal means for comparing plans by computing a measure of similarity and complexity. The development and implementation of similarity and complexity measures of 2D architectural plans has been utilised successfully for prediction purposes [Gero and Kazakov, 2001]. The following section describes a computational means of representing shapes and spatial relations symbolically and briefly summarises the information theoretic tools used in our framework, which are founded on well-known methods.

3 Encoder-Analyser

The approach is structured as follows. In considering shape and spatial recognition we decompose this problem into two stages: encoding for representing building plans in terms of morphology, topology and mereology; and matching the generated qualitative representations with known feature patterns for a particular class of design. The encoding schema corresponds to invariant coding procedures. The procedure employs qualitative descriptions of boundary- and graph-based landmarks invariant to scaling, rotation and shift in patterns. The output of the encoder acts as the input to an analysis scheme, which consists of information theoretic tools. The complete framework of the Encoder-Analyser (E-A) is shown in Figure 2.

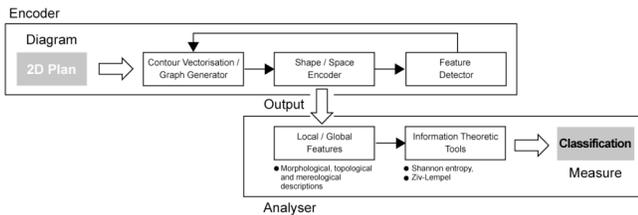


Figure 2. Encoder-analyser (E-A) framework.

The core idea is that plan drawings can be uniquely characterised by the representation of embedded shape and spatial features. Each embedded shape and spatial feature is described by qualitative values and stored as a series of symbols in a 1D string and a series of labelled graphs. Features can be identified based on semantics and string pattern matching techniques. The similarity between two design plans is then computed using Shannon entropy and Liv Zempel complexity.

3.1 Qualitative Representation Schema

The description of shapes and space in our symbolic scheme may be treated as the problem of describing distinctive characteristics at the categorical level. Since shape and

spatial characteristics can be treated as features, the representation of sketches and drawings involves recognizing, capturing and representing these features as discrete symbols. The aim of our approach is to produce multi-level canonical representations analogous to a natural language that captures information relating to the qualitative character of the building plan.

We establish shape and spatial features as classes derivable from the intersection of contours under the following conditions:

- i) *bounded rectilinear polyline shape* – a shape composed of a set of only perpendicular straight lines where for any point on its contour there exists a circuit that starts from and ends at a vertex without covering any vertex more than once. These shapes are closed, without holes and are oriented vertically and horizontally;
- ii) *primitive shape* – a shape that satisfies the conditions in (i) and is also initially explicit and thus can be input and manipulated by specifying its vertices; and
- iii) *shape aggregation* – a shape that satisfies the conditions in (i) and exist as an aggregation of two or more other shapes.

The first principle of the approach is the encoding of vertices where qualitative changes occur. The system looks at vertices of shape contours and graph edges and captures distinctive physical characteristics. On each singular vertex, a landmark value for a particular design quality (shape attribute or spatial relation) is abstracted into a single symbol.

We use standard first order logic and set membership notation with the following symbols: constants; connectives: \square (and), \square (or), \square (if... then); quantifiers: \forall , \exists ; and sets: \in (is an element of) \subseteq (is a subset of), \cup (the intersection of). This specification method provides descriptions represented in terms of position, length, relation and area.

QFB shape representation

We take the representation of shape contours and add intersection semantics to the vertices. Encoding follows where vertices are scanned and labelled in a counter-clockwise direction. As a result the symbol strings that represent the outlines of shapes are cyclic. The following three discrete stages describe the first class of qualitative representation in the schema hierarchy.

physicality \square symbol

This specification method provides a description for shape attributes represented in terms of intersection type for contours: their relative position and length. Intersection attributes are encoded into qualitative value signs at the vertex as a landmark point. Landmarks are set when a new contour is compared to the previous contour. The schema can be defined by the following in relation to a 2D plan:

Definition 1: Let ω_{χ} be a vertex, where χ is the list of contours that intersect at ω and θ the qualitative symbol value that describes its intersection type. A vertex must carry a minimum of two contours and includes both external (boundary) and internal contours.

$$\omega_{\chi} = \theta \quad (1)$$

Definition 2: (convex) Let \mathbf{L} be the symbol value produced by two contours intersecting at a vertex when viewed from (inside) the acute angle \angle .

$$\angle \left\{ \varpi(\chi \cup \chi_{+1}) \right\} \square \theta = \mathbf{L} \quad (2)$$

Definition 3: (concave) Let $\mathbf{\bar{L}}$ be the symbol value produced by two contours intersecting at a vertex when viewed from the complementary angle \angle .

$$\text{comp} \angle \left\{ \varpi(\chi \cup \chi_{+1}) \right\} \square \theta = \mathbf{\bar{L}} \quad (3)$$

As a consequence of the nature of the intersection types two shapes that look geometrically different may nonetheless have the same qualitative description. An example is shown in Figure 3, where a sample of geometrically different shapes are described by the sequence: $\mathbf{L}, \mathbf{L}, \mathbf{L}, \mathbf{L}, \mathbf{L}, \mathbf{\bar{L}}, \mathbf{\bar{L}}, \mathbf{L}$ (commencing at landmark \mathbf{L} for all three shapes).

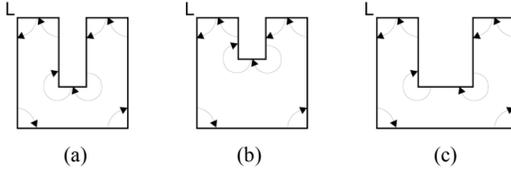


Figure 3. U-Shape examples $\mathbf{L}, \mathbf{L}, \mathbf{L}, \mathbf{L}, \mathbf{L}, \mathbf{\bar{L}}, \mathbf{\bar{L}}, \mathbf{L}$

Geometric differences are included by adding three auxiliary attributes for relative lengths of segments [Gero and Park, 1997]. Definitions 1 and 2 are annotated with a symbol value indicating relative length. The landmark provides a ratio to distinguish the relative difference under the labels of *equal to*, *greater than* or *less than*. These auxiliary codes describe lengths between the previous contour and the current contour. We define equal to: $\theta_=$; greater than: $\theta_>$; and less than: $\theta_<$; where θ is the qualitative symbol value \mathbf{L} or $\mathbf{\bar{L}}$. Thus in Figure 3, shape (a) is described by the sequence: $\mathbf{L}_>, \mathbf{L}_=, \mathbf{L}_=, \mathbf{L}_<, \mathbf{L}_>, \mathbf{\bar{L}}_<, \mathbf{\bar{L}}_>, \mathbf{L}_<$; shape (b) is described by: $\mathbf{L}_>, \mathbf{L}_=, \mathbf{L}_=, \mathbf{L}_<, \mathbf{L}_=, \mathbf{\bar{L}}_<, \mathbf{\bar{L}}_>, \mathbf{L}_=$; and (c) is described by: $\mathbf{L}_>, \mathbf{L}_>, \mathbf{L}_<, \mathbf{L}_<, \mathbf{L}_>, \mathbf{\bar{L}}_<, \mathbf{\bar{L}}_>, \mathbf{L}_<$.$

Where there is contact of more than two contours at a single vertex, the representation of shape attributes is transformed [Gero and Jupp, 2003]. Vertices of this type can be described by one of the following three qualitative symbol values describing intersection type.

Definition 4: (straight + two right angles) Let \mathbf{T} be the symbol value produced by three contours intersecting at a vertex when viewed from (inside) either of the two acute angles \angle .

$$\angle^\varphi, \angle^\kappa \left\{ \varpi(\chi \cup \chi_{+1} \cup \chi_{+2}) \right\} \square \theta = \mathbf{T} \quad (4)$$

Definition 5: (complement of straight + two right angles) Let $\mathbf{\perp}$ be the symbol value produced by three contours intersecting at a vertex when viewed from the complementary of the two acute angles \angle .

$$\text{comp} \angle^\varphi, \angle^\kappa \left\{ \varpi(\chi \cup \chi_{+1} \cup \chi_{+2}) \right\} \square \theta = \mathbf{\perp} \quad (5)$$

Definition 6: (four right-angles and its own complement) Let $\mathbf{+}$ be the symbol value produced by four contours intersecting at a vertex when viewed from the inside any of its acute angles \angle .

$$\angle^\varphi, \angle^\kappa, \angle^\lambda, \angle^\mu \left\{ \varpi(\chi \cup \chi_{+1} \cup \chi_{+2} \cup \chi_{+3}) \right\} \square \theta = \mathbf{+}$$

A distinction is made between morphological descriptions ($\mathbf{L}, \mathbf{\bar{L}}$) and topological descriptions ($\mathbf{T}, \mathbf{\perp}$, and $\mathbf{+}$) where the latter focuses on concepts of connectedness that emerge from descriptions of shape aggregation. Thus, a critical difference exists in the scanning and labelling of vertices for aggregated shapes. Isolated shapes (and embedded shapes) contain vertices with only two contours each (see examples in Figure 4 (a) and (b)), and therefore have one scanning direction. Aggregated shapes can contain vertices with three or four contours i.e. multi-region vertices, and therefore have more than one scanning direction, Figure 4.

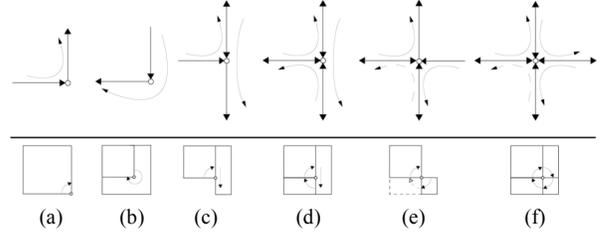


Figure 4. Scanning directions

Figure 4 illustrates vertices involved in one (a), two (b), (c) and (e), three (d), (e) and (f) or four (f) regions.

symbol \square regularity

The physicality and connectivity of a shape is described as a sequence of symbols which is assumed to denote design characteristics of a building plan. Some of these characteristics are easy to identify from structural regularities in symbol strings, while others are more difficult because they appear in more complex patterns. Transformation from sequences of symbols (unstructured) to regularities (structured) brings interpretation possibilities.

Patterns that reflect basic repetitions and convexity are: indentation, protrusion, iteration, alternation and symmetry. Iteration refers to a repetition of patterns with no interval; alternation refers to a repetition of patterns with irregular intervals; and symmetry refers to a reflective arrangement of patterns (not necessarily expressed as visual symmetry). The five syntactic regularities and definitions are listed below.

Definition 7: (indentation) Let \mathbf{I} be the symbol for indentation where v is an integer:

$$\mathbf{I} = \mathbf{L} \ v \ (\mathbf{\bar{L}}) \ \mathbf{L} \quad (7)$$

Definition 8: (protrusion) Let $\mathbf{\Pi}$ be the symbol for protrusion where v is an integer:

$$\mathbf{\Pi} = \mathbf{\bar{L}} \ v \ (\mathbf{L}) \ \mathbf{\bar{L}} \quad (8)$$

Definition 9: (iteration) Let \mathbf{E} be the symbol for iteration where v is an integer:

$$\mathbf{E} = v \ (\mathbf{L}) \ \square \ v \ (\mathbf{\bar{L}}) \ \square \ v \ (\mathbf{T}) \ \square \ v \ (\mathbf{\perp}) \ \square \ v \ (\mathbf{+}) \quad (9)$$

Definition 10: (alteration) Let \mathbf{A} be the symbol for alternation where v is an integer:

$$\mathbf{A} = v \ (\mathbf{L}) \ \square \square \ v \ (\mathbf{\bar{L}}) \ \square \square \ v \ (\mathbf{T}) \ \square \square \ v \ (\mathbf{\perp}) \ \square \square \ v \ (\mathbf{+}) \quad (10)$$

Definition 11: (symmetry) Let Σ be the symbol for symmetry where v is an integer, δ is the class descriptor and $comp\delta$ is the complement of δ :

$$\Sigma = \{v(\delta) \square comp\delta\} \quad (11)$$

A pattern of symbol sequences can denote specific categories of shape classes that are well known or familiar in contour.

regularity \square feature

Syntactic regularities identified from symbol sequences become shape features. Discovering visual patterns plays an important role in organising and providing order and is known also as shape semantics. Shape features are recognised by matching symbols with an existing feature knowledge base. Since shape features are derived from basic neighbouring shape elements we describe them as local. The five syntactic regularities listed above define five atomic local shape features, i.e., indentation, protrusion, iteration, alternation and symmetry.

Conceptual units are also defined for LSF, which correspond to how they can be chunked. These units define four discrete levels [Gero and Park, 1997]. The terminology used for these conceptual units correspond to terms used in natural language. Conceptual units and their definitions are provided in Table 1.

TABLE 1. Conceptual units. (after Gero and Park, 1997)

Unit	Definition
Word	Sequence referring to a shape pattern with a particular design meaning
Phrase	Sequence in which one or more words show a distinctive pattern of structural arrangement
Sentence	An aggregation of words and phrases so that it refers to a closed and complete shape contour
Paragraph	A group of sentences where an aggregation of shapes are described without any spatial relationships

Local shape features are used as the basis for reasoning about design plans. For example, it is possible to determine categorical information about shapes, since by identifying syntactic regularities patterns can be compared. In the following section we extend this schema to include spatial relations by abstracting two additional levels of information.

QFB Spatial Representation

The formal treatment of visual languages is often based on graph representations. In the following we utilise graphs in order to represent spatial information. We maintain our analogy with language since by generalising descriptions of both adjacency and area in to a QFB language we are essentially moving from symbols related by one relationship (linear ordering given by sequencing) to multiple relationships which can be represented by graphs. Further, in assuming that plans can be represented by graphs, a spatial language is a set of such graphs abstracted from the original contour representation. The aim of constructing spatial descriptors as a second hierarchy of a qualitative codes is to produce spatial (global) features.

Graph Diagrams Designed for Representing Topology

The QFB approach to spatial descriptors is based on graph diagrams derived from the original contour representation. Graphs abstracted from contours are able to represent spatial topologies, which denote adjacency [Mantyla, 1988]. Graphs as duals of the spatial layout are constructed by locating new vertices in the centres of all bounded rectilinear polyline shapes, as well as one other vertex within the external region or background of the plan.

Using this approach we examine two types of spatial relations. First, symbol values derived to represent properties of adjacency. Second, symbols are derived for area descriptions of regions. Figure 5 shows the original contours in (a) the location of vertices in (b) and graph diagram (c).

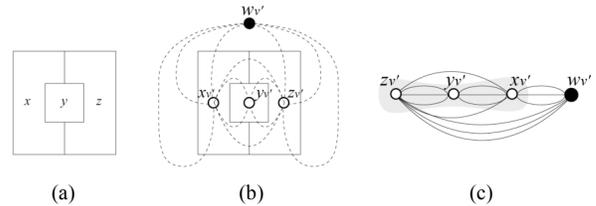


Figure 5. (a) Shapes X, y and Z, (b) location of vertices and edges, Wv' , Xv' , Yv' , Zv' ; and (c) sequenced graph diagram

We consider how to define syntax and semantics from these graphs. In particular we ignore all structural constraints and simply regard the QFB language as a set of graph diagrams. We utilise symbol values produced in the previous level as our principal building blocks. In keeping with the previous three discrete stages we present the second level of representation in the same format.

physicality \square (dyad) symbol

Let us define an abstract syntax for QFB spatial descriptions of graphs.

Definition 12: Let G be an undirected graph with vertices ω' located at centre of regions ρ and where edges ϵ have a mapping defining for each edge the vertices it connects.

$$\epsilon \subseteq \omega', \omega' + 1$$

After a graph is constructed it must then be sequenced [Kaufmann, 1984] and labelled. The term topology network is used to label such a labelled graph. We label each edge with a pair of symbols; derived from the values of the previous level (for intersection), i.e., L , \lrcorner , T , \perp , $+$. Therefore, labels assigned to edges correspond to the labels of the two vertices belonging to a shape contour. Edge labels are defined by the following:

Definition 13: Let $\delta\sigma$ be the set of dyad symbols for vertices

$$\omega_x, \omega_{x+1} \quad \delta\sigma \subseteq \{(L, \lrcorner, T, \perp, +) \square \square (L, \lrcorner, T, \perp, +)\} \quad (13)$$

Edges can be labelled therefore with one of 15 dyad symbol values to produce an adjacency description. The 15 dyad symbols have auxiliary symbol values indicating the relative area of regions.

Definition 14: Let a regular polygon be a region ρ and have an area α that is represented at the vertex ϖ' . The area of a regular polygon with n sides and side length s is given by

$$\alpha_{n-gon} = 1/4 ns^2 \cot(\pi/n) \quad (14)$$

A landmark is set to the numeric point of the magnitude of adjacent region areas providing a ratio to distinguish the relative area under the labels of *equal to*, *greater than* or *less than*, or *infinite* for all external vertices. We define equal to: $\delta\sigma_{=}$; greater than: $\delta\sigma_{>}$; less than: $\delta\sigma_{<}$; and infinite: $\delta\sigma_{\infty}$; where $\delta\sigma$ is the qualitative dyad symbol value. If vertex ϖ' is external define $\alpha = \infty$.

Continuing the example given in Figure 5 we illustrate these mappings in Figure 6. Figure 6(b) shows four vertices: $w\varpi'$, $x\varpi'$, $y\varpi'$, and $z\varpi'$, ($w\varpi'$, is an external vertex), eight edges and six new (abstract) regions.

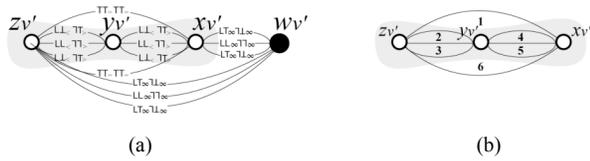


Figure 6. (a) Network: sequenced and labelled graph and (b) six new regions.

In Figure 6 (a), edges are labelled according to the intersection type of the two vertices belonging to the contour it crosses (a dyad symbol) as well as the values describing the relative area of regions. Graph vertex labels are not required and thus abstract syntax is produced only for edges by the set $\delta\sigma$ and $\{= ; < ; > ; \infty\}$. This specification method provides a description for spatial attributes in terms of adjacency and area descriptors. In order to analyse the topology network semantics are defined.

symbol \square regularity

The representation of dyad symbols reveals distinctive topological characteristics that can be recognised from syntactic regularities. Some of these characteristics are easy to identify, while others are more difficult. Unlike the morphological characteristics, topological characteristics contain variations depending on the viewpoint (orientation) of \top and/or \perp intersections. Depending on their orientation, these dyad symbols can define two types of adjacency.

Topological features recognised in syntactic regularities of dyad symbols include: *complete adjacency*, *partial adjacency* and *offset*. Complete adjacency refers to a region having total adjacency along a boundary with another region; partial adjacency refers to a region having only incomplete adjacency along a boundary with another region; and offset refers to a region having adjacency shared along more than one boundary with another region. Definitions for adjacency regularities are provided:

Definition 15: \mathbf{X} is a set of the $\delta\sigma$: $\{L; \top; +\} \square \square \{L; \top; +\}$; where \mathbf{X} is a semantic symbol value denoting complete

adjacency, and the set $\{\kappa\}$ is labelled according to intersection type:

$$\mathbf{X} \subseteq \left\{ (L \square L); (\top \square \top); (+ \square +); (L \square \top); (\top \square +); (L \square +) \right\} \quad (15)$$

Definition 16: \mathbf{P} is a set of the $\delta\sigma$: $\{L; \top; \perp; +\} \square \square \{L; \top; \perp; +\}$; where \mathbf{P} is a semantic symbol value denoting partial adjacency, and the set $\{\kappa\}$ is labelled according to intersection type:

$$\mathbf{P} \subseteq \left\{ (\top \square \top); (\top \square \perp); (\perp \square \top); (\perp \square \perp); (\top \square +); (\perp \square +); (L \square L) \right\} \quad (16)$$

Definition 17: \mathbf{O} is a set of the $\delta\sigma$: $\{L; \top; \perp; \perp\} \square \square \{L; \top; \perp; \perp\}$; where \mathbf{O} is a dyad symbol denoting offset, and the set $\{\kappa\}$ is labelled according to intersection type:

$$\mathbf{O} \subseteq \left\{ (\top \square \top); (L \square \top); (\top \square \perp); (\top \square \perp); (\perp \square \perp) \right\} \quad (17)$$

Note: * denotes an exception, defined by the orientation of the intersection type relative to the adjacent region. Adjacency and area descriptions form semantic strings which are not oriented. All regions have four or more adjacency symbol values.

Topological features identified for the example from Figure 5 are illustrated in Figure 7. Figure 7(a) shows the six abstract regions and Figure 7(b) features identified from their dyad symbol values.

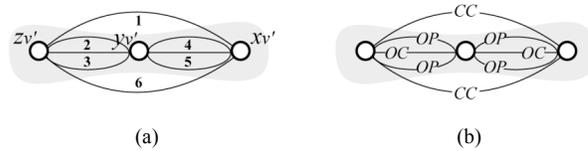


Figure 7 (a) Network: sequenced and labelled graph and (b) six new regions.

In Figure 7(b), edges are labelled according to their feature set. The relations defined above can now be described symbolically, such that the spatial relationships can now be described semantically. Shape x to Shape y is offset and represented by O ; Shape x to Shape z has complete adjacency and represented by X ; Shape y to Shape x and z has complete and partial adjacency and represented by X and P ; Shape z to Shape x has complete adjacency and represented by X .

regularity \square feature

From the representation of dyad symbols we are able to add a level to the way in which we may reason about the plan. Semantic regularities identified in dyad symbols produce spatial features termed global since neighbourhoods include multiple regions. Like local shape features, global spatial features are labelled by matching an existing feature knowledge base. The topological features identified at this second level are the first of two kinds of GSF and provide a basis for reasoning about spatial relations.

It becomes possible to determine categorical information about shape aggregations in spatial terms. The three syntactic regularities defined above can be seen as three spatial feature categories. Commonalities between these

topological characteristics can be determined by comparing matchings.

Dual Networks Designed for Representing Mereology

Graphs are useful in organising 2D drawings because different types and levels of features can be abstracted. In the previous section information about topological relations was abstracted from graph diagrams to produce topology networks, where labels are drawn from a finite alphabet. In this section we use the dual of the topology network to derive composite symbol values describing relations of contact and organisation. A topology network's dual is constructed by locating new vertices in the centres of all abstract regions whose edge does not connect with the external vertex. Using this approach we examine additional descriptions of spatial relations. The network in Figure 7(a) may be re-represented by abstracting its dual. Figure 8(a) shows the topology network and (b) shows the dual topology network consisting of six new vertices ($f-k$), and six edges.

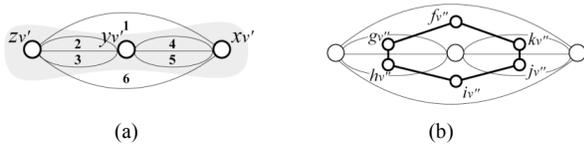


Figure 8. (a) Topology network and (b) dual topology network.

We consider how to define syntax for the dual since topological features identified at the previous level can be translated further into meaningful spatial semantics. In order to do this we utilise the concept of mereology.

Mereology is an attempt to lay down the general principles underlying the relationships between a whole and its parts. The relations have been formally defined by thirteen interval relations [Allen, 1984] for the temporal domain. This has allowed the formulation of ontological laws pertaining to the boundaries and interiors of wholes as well as to relations of contact and organisation [Aurnague and Vieu 1993]. Since we are only interested in those instances where identities are in contact, the notions of “before/ after” do not apply here. Further, because of constraint conditions the relations: “starts/ started-by”; “finishes/ finished-by”; “during” and “equals” are also not applicable. As in the previous two levels we use the same three discrete stages to present the final level of representation.

physicality \square composite symbol

Let us define an abstract syntax for QFB spatial descriptions of dual networks.

Definition 18: Let DN be a dual network with vertices ϖ' located at centre of abstract regions ρ' and where new edges ε' have a mapping defining for each edge the vertices it connects.

$$\varepsilon' \subseteq \varpi', \varpi' + 1 \quad (18)$$

By constructing the dual of a topology network it is possible to abstract additional information. The dual carries

with it a description of higher-level mereological relations. For each new edge labels are derived from the features identified at the previous level for topology, i.e., X, P and O, and correspond to graph edges $G(\varepsilon)$. By taking the dual, composite symbol values are produced. Composite symbols are specified for organisation identities, Definitions of the three semantic regularities are provided below:

Definition 19: $\chi\sigma$ is a subset of topology feature types: $\{X \square P \square O\}$; where $\chi\sigma$ is a composite symbol value, and is labelled according to feature symbols:
 $\chi\sigma \subseteq \{(X P); (X O); (PP)\}; \{(XX)\}; \{(PO); (OO)\}$ (19)

This specification method provides a description of a 2D plan relating to mereology.

composite symbol \square regularity

Definitions for basic semantic interpretations have been developed in order to reason about rectilinear spatial properties. Composite symbols allow semantic regularities to be identified. Dual networks are undirected and as a consequently regularities in composite symbols identify three pattern types: “overlaps/ overlapped-by”, “meets/ met-by”, and contains/ contained-by”. Definitions for contact-organisation identities are given below.

Definition 20: (*Overlaps/ Overlapped-by*) Let ς be the symbol for overlaps/ overlapped-by with v an integer.
 $\varsigma \subseteq \{(X P) \square (X O) \square (PP) \square (PO) \square (OO)\};$
 $v \leq 2 \{[(PO) \square (OO)]\}$ (20)

Definition 21: (*Meets/ Met-by*) Let M be the symbol for meets/ met-by with v an integer.
 $M \subseteq \{v(XX); v(XX) \square (PO) \square (OO); v(XX) \square v(XP) \square (XO) \square (PP);$
 $v(XX) \square v(XP) \square (XO) \square (PP) \square (PO) \square (OO)\}$ (21)

Definition 22: (*Contains/ Contained-by*) Let Y be the symbol for contains/ contained-by with n an integer.
 $Y \subseteq \{v(PO) \square (OO) \square (XO); v > 2(XP) \square (XO) \square (PP);$
 $2(PO) \square (OO) \square (XP) \square (XO) \square (PP); v(XX) \square v(PO) \square (OO);$
 $v(XX) \square v(XP) \square (XO) \square (PP) \square v(PO) \square (OO)\};$ (22)

Referring to the example, the relations defined above can now be described symbolically. Figure 9(a) shows the topology network and Figure 9(b) shows the dual topology network consisting of six new vertices ($f-k$), and six edges.

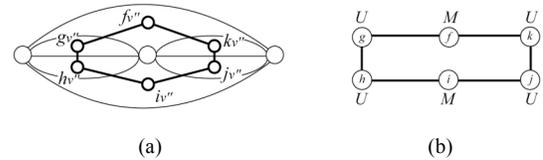


Figure 9. (a) Topology network and (b) dual topology network.

Spatial relationships between abstract regions $f, g, h, i, j,$ and k (from shapes x, y and z) can now be described semantically as meets/ met-by and represented by M , and contains/ contained-by and represented by Y .

regularity □ feature

Once regularities of syntax patterns have been identified, each pattern is categorized. The three syntactic regularities defined above can now be seen as three spatial feature categories, i.e., overlaps/ overlapped-by, meets/ met-by, and contains/ contained-by. In addition to identifying mereological relations, it is possible to use these as features for the purposes of reasoning about the 2D plan as a whole.

This three class schema forms a hierarchical qualitative language for 2D architectural plan drawings that describes information about both shape and spatial relations in terms of shape structure, arrangement, area and organisation.

3.2 Applying Information Theoretic Measures

An information theoretic approach to the estimation of similarity and complexity is applicable to qualitative representations with discrete alphabet labels. Once a drawing is encoded in this canonical form we are able measure 1D strings and networks. We use two measures provided by classic information theory: Shannon entropy and Ziv-Lempel complexity. Each of these measures provides an integral value over the whole drawing or set of drawings of its information content. The drawing's complexity is defined by the amount of information within the 1D string and graph structure. The similarity between plan drawings can be defined as the degree of similarity between them.

Gero and Kazakov [2001] describe the intuitive idea behind this approach as the more information necessary to describe the particular drawing the higher its complexity and the closer to each other are the distributions of features in two shapes, the higher is the degree of similarity between them.

The entropy is calculated as:

$$En = - \sum_{i,j} PS(q_i, q_j) \log \text{ProbM}(q_i, q_j) \quad (23)$$

Where $PS(q_i, q_j)$ is the empirical probability of the symbol q_i following q_j in this sentence.

Entropy is a measure that can only be calculated for an ensemble of similar sequences. Thus, if we have a group of similar drawings we can calculate entropy for each symbol sequence. Those that have higher entropy values will be declared as more complex than the ones with the lower values of entropy. For different groups of drawings the comparison between the 1D strings as well as between network matrices can be carried out by computing perplexity. Perplexity, PP , is defined as:

$$PP = 2^{En} \quad (24)$$

The higher the perplexity the further apart are the two generators from each other and less similar are the two strings being compared. When perplexity of one corpus of symbol strings is computed with respect to the other corpus, the mean "distance" between corpuses can be obtained.

The usefulness of Shannon entropy as a complexity measure is limited since it is applied to the process generat-

ing the string or matrix rather than to the resulting string or matrix itself. Lempel-Ziv compression, (LZ), as a complexity measure is utilised as it is defined by the string or matrix itself rather than processes that created them. We use LZ to show how drawings can be used to track changes over time.

The measure LZ [Ziv and Lempel, 1978] is essentially the number of cumulatively distinct words in the symbol string descriptions and determines how far a description can be compressed. The heuristic idea is that the most complex drawings are those ones whose description cannot be compressed. LZ can be computed for individual plan drawings can be used to compare local and global features belonging to different categories, and is valuable as a measure of style.

4. Experiment

We describe an experiment that evaluates the three hierarchical qualitative representations for the prominent twentieth century architect Frank Lloyd Wright. The sample of Wright's residential designs used in this experiment spans five decades and is plotted in Figure 10.

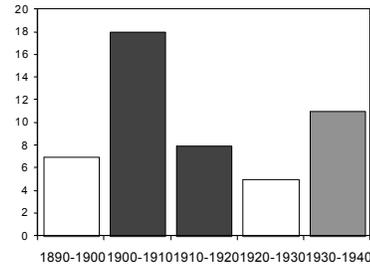


Figure 10. Wright's residential projects over number of decades.

Decades shown as shaded white represent what we refer to as Wright's *Early* and *Transition* periods. Decades shown as shaded dark grey and light grey represent the two periods described by critics and historians as *Prairie*, spanning two decades and *Usonian*. Prairie and Usonian periods are significant since they are identified historically as 'styles'. Figures 11 and 12 illustrate plan drawings typical of Wright's Prairie and Usonian designs.

(a) (b)

Figure 11. Wright’s plan drawings: (a) and (b) Prairie

(a) (b)

Figure 12. Wright’s plan drawings: (a) and (b) Usonian.

Prairie houses are characterized by horizontal lines reflected in the geometries of 2D plans. Typically, they consist of open spaces instead of strictly defined rooms. The Usonian style represented a change in domestic planning where the living and dining room were unified and the kitchen was only partially separated.

A total of 49 plans [Wright, 1944] were coded in the three hierarchical languages: morphology, topology and mereology. The resulting symbol 1D strings and networks were separated into groups that belong to the different decades in which they were designed. Each plan description was analysed and perplexity and compression calculated. At the very least we expect the E-A model to be able to differentiate between Wright’s Prairie and Usonian designs for one or more of the three qualitative descriptions. This is based on the assumption that there have been changes in the complexity of drawings Wright produced during these decades. In other words the corresponding measures for 2D plans must be statistically different for one or a combination of the three shape and spatial descriptions.

Similarity measure for FLW

The mean or overall perplexities of the plan drawings from the different decades for Wright are shown in Table 2.

TABLE 2. The perplexities of Wright’s plans from 1890-1940
Columns denote data sets and rows denote string type.

	Early 1890-1900	Prairie 1900-19 10-1920	Transition 1920-1930	Usonian 1930-1940
Morphology	2.03	2.23	2.27	2.25
Topology	4.02	5.12	5.20	4.30
Mereology	2.97	3.21	3.20	3.33

From the table we can see minor variations within the measure of perplexity for morphology and mereology, indicating strong similarity in Wright’s shape morphologies as well as spatial mereology. Topology perplexity varies more significantly, indicating that Wright’s topology varied in all of the four major periods. This is the case for both described styles: Usonian and Prairies; where for Prairie topological perplexity remained steady over the two corresponding decades. We can see for these two decades that the morphological and mereological perplexity also

remained steady, where for the first Prairie decade the perplexities were: 2.23 / 5.12 / 3.21 and the for second decade were: 2.27 / 5.20 / 3.20. These results imply that the morphology, topology and mereology features in Wright’s Prairie designs did not significantly change over time.

Complexity measure for FLW

The results of LZ complexity for Wright’s residential designs are shown in Figure 13. The figure contains three graphs that show the empirical dependence on decades of the LZ and their polynomial regressions.

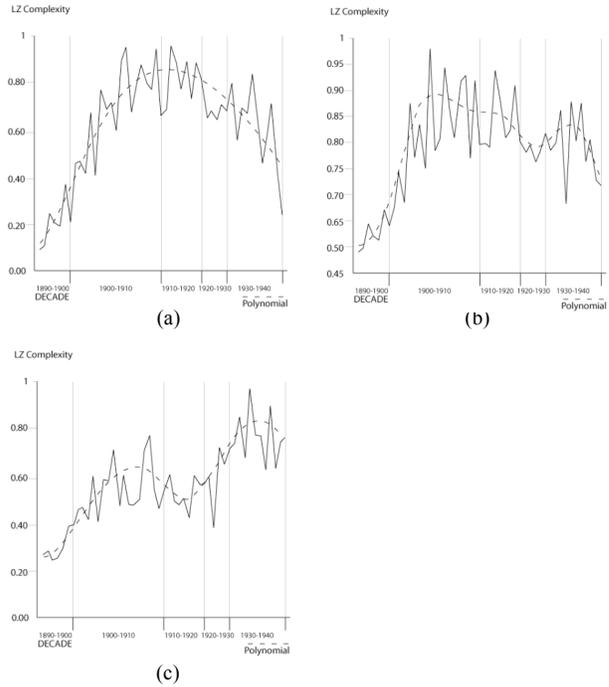


Figure 13. The dependence of LZ on time for (a) morphology, (b) topology, (c) mereology.

Figure 13(a) indicates that the complexity of plan morphology steadily increased then decreased in the following decade and continued to decrease from 1930 to 1940. This shows that the morphological complexity was highest during the two decades of the Prairie style than it was for the decade of the Usonian style. In Figure 13(b) we can see that the topological complexity increased steadily from the 1890s, peaking around the mid 1910s with the Martin House (1904). From 1910 to 1930, topological complexity decreased, and then slightly increased again from 1930 to 1940 during Wright’s Usonian style. Figure 13(c) indicates the change in complexities for mereology, where a steady increase throughout the length of Wright’s practice and a slight trough occurring in the second decade of the Prairie style and into the Transition period.

From these results we can identify how the morphological, topological and mereological features characterise each decade and distinguish design periods. Table 3 illustrates the patterns of change characterised by

the complexity levels: low, medium and high which are scaled on the basis of number of standard deviations.

TABLE 3. Change patterns in Wright’s plans for morphology, topology and mereology.

	Morphology	Topology	Mereology
Early 1890-1900	LOW	LOW	LOW
Prairie 1900-1910	MEDIUM	HIGH	MEDIUM
Prairie 1910-1920	HIGH	HIGH	MEDIUM
Transition 1920-1930	MEDIUM - HIGH	MEDIUM - HIGH	LOW - MEDIUM
Usonian 1930-1940	MEDIUM - HIGH	LOW - MEDIUM	HIGH

Table 3 shows the overall computed measure of each decade for Wright’s plans and makes specific predictions between rows about the similarity of different styles for morphological, topological and mereological features. These results imply that the E-A model presented here provides the potential to reveal patterns of change for related designs. Measures of complexity obtained at both local and global levels can be used to distinguish one design from another. This is significant since in differentiating designs, individuals may evaluate the similarity of certain design attributes (e.g. local features: iteration, indentation, etc.) more than other attributes (e.g. global features: contains/contained-by, etc.).

In this study the patterns of change identified for Wright’s local and global features the Prairie ‘style,’ which historically grew to dominate the design population, is shown to have distinct and consistent shape and spatial characteristics. By examining changes at key design periods transitions from one dominant ‘style’ to another can be associated with substantial change at a single point. We propose that categories that can be derived from the E-A model characterize the scale at which transformations occur.

5. Discussion

The E-A model enables identification of shape and spatial semantics and measures their similarity and complexity. Descriptions of shape and space are tested as a problem of representing and measuring stylistic discriminators at the categorical level. The E-A model is capable of distinguishing between designs at a variety of levels. Previous approaches of 2D plan comparative analysis’ have relied only on one level of information and modelled only the outline contour of plans. Our preliminary study indicates that the qualitative representational schema can potentially be used to identify stylistic discriminators for shape and space providing additional levels of reasoning about a designer’s style. Further insights into 2D design transformations and drawing styles may be gained by examining the differences in 2D plans between two or more architects.

The dynamics identified within the results of the experiment give rise to characteristics common in the architectural domain in their demonstration of patterns of continuous change through time, and approximately constant design diversity at any instant. Although it is of

considerable theoretical interest, the patterns identified in Wright’s residential designs have important implications for designers in demonstrating its effectiveness of the model in evaluating changes in 2D plan designs and suggests a more systematic approach to prediction.

In addition, the kinds of features that designers and critics exploit for design differentiation can be identified formally in an automated fashion. Moreover the qualitative description of salient pictorial features as symbols and as patterns of symbols provides the basis for representation and reasoning about drawing style.

6. Conclusion

Our investigation of style in architecture focused on representation (encoding) and classification (analysis). We highlight the following two contributions of this work: (1) a schema of qualitative representation and for 2D plan drawings and (2) a formal model of feature recognition and classification based on features at both the local and global levels. Encoding and analysis of shape and spatial relations requires multi-level processing and is dependent on abstract knowledge that incorporates design semantics.

The E-A model provides the basis for new kinds of design tools. Research shows that the reasoning skills required to read architectural drawings are learnt by individuals and vary between viewers, such as between novice and expert designers [Kavakli, et. al, 1999]. Current CAD systems are unable to aid the designer in the perception of figures and gestalts and in the recognition and categorisation of shape and spatial characteristics. A formal characterisation of 2D architectural style is significant to the development of such conceptual design tools for automated classification and information retrieval.

Recognition of design features and similarities influences designing since it enables the designer to extend design knowledge by grouping or classifying according to some distinguishable properties. The approach presented in the E-A model can assist designers in useful ways by “amplifying the mind’s eye” [Fish and Scrivener, 1999]. The ability to automatically identify visual similarities makes past designs relevant to present ones and consequently information about a design can be categorized and re-categorised.

A fully automated approach to classification of a variety of shape and spatial features like that presented here is required if the advantages of computer-aided design and planning is to be exploited in support systems. Our approach to encoding and analysis forms the basis of a computational characterisation of 2D architectural style. We believe that this perspective has the potential to provide insight into several aspects of architectural style and in particular its role in drawing.

Acknowledgements

This research is supported by an Australian Postgraduate Award. Computing support is provided by the Key Centre of Design Computing and Cognition.

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This is a copy of the paper: Jupp, J and Gero, JS (2005) Towards computational analysis of style in architectural design, *Journal of the American Society for Information Science* (to appear)