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Using logic to specify shapes and spatial relations in design grammars

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Abstract

Shape algebraic representations provide several advantages over more traditional geometric representations. The use of predicate logic formulations of shape and spatial relations provides a natural, intuitive way to extend shape representations of the shape grammar formalism to provide generalized, parametric grammars.

Introduction

Research in the use of grammars and similar production systems for design has been ongoing for several decades. Many different approaches to the problem of design generation have been attempted. All, however, must deal with the basic elements of any grammar or production system, neatly categorized in (Gips, Stiny, 1980) in terms of 1) the objects to which they apply; 2) the way they are defined; 3) the interpretive mechanism used to apply the productions, and 4) the objects they generate.

The author’s primary interest is in the representation of objects in such a system, in the belief that the underlying object representation should be the major consideration in the development of a production system. The representations used in shape grammars (Stiny, Gips, 1972) bear this out by demonstrating significant advantages over more traditional representations.

The problem of predetermination

The ‘kit-of-parts’ approach to design, generally considered an efficient method of generating designs, tends to force the designer into a specific manner of representing and manipulating objects. Thus, the structure of a model must be decided at the start. This can be considered a reductionist philosophy, in which the universe is considered to be composed of separate parts which, in various combinations, make up the whole.

However, it is extremely difficult, if not impossible, to anticipate all possible ways in which one might wish to view or classify parts of a model. This often requires an unmanageable amount of information. The problems with this approach were among the causes of the failure of early CAD building modeling systems in the 1970’s and early ’80s, which often required the predetermination of all types of information of interest, and for this information to be stored in a single model.

On the other hand, a holistic philosophy considers the universe to be a whole rather than the sum of its parts. A system which forces no preconceived structure upon the user, but rather, allows one to find all sorts of emergent features and properties from within the whole, would be extremely desirable.

Shape algebras and shape grammars in design

The algebras of shape as defined by Stiny (1991) can support both holistic and reductionist views. By considering shapes as finite sets of elements which can carry fixed properties, a reductionist view is supported. The real power of such algebras, however, lies in the fact that the elements of a shape and their properties may be defined in such a manner as to enable the emergence of features which are not apparent in the initial formulation of a shape. In addition, the generality of their representations, their reliance upon a minimum of structure, and their use in combination can provide the semantic richness needed for design generation and analysis. The practicality of these algebras has been demonstrated with their use in a wide variety of shape grammars which generate languages of designs.

While remaining true to the formal representations, these tend to be paper and pencil exercises, as the computational issues in computer implementation are great. Due to these limitations, computer implementations of shape grammars (and indeed, design systems in general) tend to simplify the formal representations in order to solve the computational problems. Attempts at implementing a shape grammar system supporting emergence tend to have other restrictions limiting their use in practical applications (Chase, 1989; Krishnamurti, 1980; 1981; Krishnamurti, Giraud, 1986; Tapia, 1996).

Logic as a specification tool

Previously, most of the shape grammar literature has dealt with the development of grammars, focusing on specific languages of designs. The representations used tend to describe shapes and spatial relations simply by drawing them, thus limiting much of the description to non-parametric shapes. With few exceptions, discussion of parametric shapes and grammars has been limited to natural language descriptions of the conditions placed upon a shape and very general descriptions of rule application.

Representing shapes and spatial relations in first order predicate logic provides an easy way to develop complete computer systems for reasoning about designs. The use of logic provides a natural, intuitive method of generating precise definitions of parametric shapes and high level spatial relations. Its use as a specification and programming tool has become widespread over the past two decades, providing advantages over traditional procedural programming methods, among those the ability to specify the knowledge to be encapsulated in a model (description) without the need to specify data manipulation procedures (prescription) (Kowalski, 1979). The use of logic can facilitate a top-down method of systems development, from the abstract to the specific. The symbolic abstractions of logic formulations enable one to denote entire classes of data structures and procedures while ignoring their details. This can be a more natural method of development than having to deal with often unintuitive formulations.

The use of logic in design is not new; general surveys include (Coyne et al., 1990) and (Mitchell, 1990). Some examples include its use in shape grammar and reasoning systems (Chase, 1989; Damski, Gero, 1996; Heisserman, Woodbury, 1994; Krishnamurti, 1992a; 1992b; Krishnamurti, Giraud, 1986). The weaknesses of the shape grammar implementations are in their limitations due to computational problems; those of other logic based systems are in their representations of design objects, which—with few exceptions—cannot support emergent features.

Rather than attempt to solve all of these problems, the focus here is on the representations rather than the search and control issues inherent in any production system. The approach taken is of modeling designs using spatial relations based upon shape algebraic representations. This entails the construction of a formal, hierarchical model of shape, spatial relations and non-spatial properties from first principles of geometry, topology and logic. Parametric definitions of shape and spatial relations which are more general and precise than previous definitions have been created by extending the shape algebra formalisms with the use of logic. These relations can be used to describe designs in more ways than simply geometrical composition: they have the potential to represent behavioral, psychological and cultural issues.

Shapes and spatial relations

The focus here is mainly on topological properties of shapes, with the assumption that underlying data structures and low level computations are implementable for geometric shape description. By constructing a hierarchy of spatial elements (points bound lines, lines bound regions, etc.), general definitions for spatial relations which apply to multiple element types can be developed. In this way, spatial relations are parameterized and can apply to shapes in any dimension. For example, a single definition of the relation *share_boundary* between two elements of the same type can be used for both lines, regions, solids, etc. by examining the product (•) of the elements' boundaries (Chase, 1996):

$$\forall A \forall B\, [share\_boundary(A,B) \leftrightarrow boundary(A) \bullet boundary(B) \neq \emptyset]$$

In the course of this research, a large set of spatial relations and operations has been constructed from a base set of primitive definitions. These include standard geometric concepts such as *parallel*, *distance*, *projection*, as well as interesting extensions to a basic *intersection* operation. These general relations and operations can be used to fashion domain specific relations and queries.

Applications

Preliminary work by the author in modeling spatial relations has been done in the domains of geographic information systems (GIS) and architectural plans (Chase, 1996). GIS in particular provides a good testing ground for the spatial relations developed in that two dimensional maps contain simple relations between points, lines and regions. Current GIS systems tend to model a fixed set of features; the possibility of emergent features and properties in such systems is limited or nonexistent. In the course of this research, comparisons with traditional GIS systems have been made, and several types of emergent features have been identified.

Implementation issues

The method for modeling designs introduced here is descriptive, rather than operational in manner. In this way, the focus is on the logic of the relations between objects rather than the specification of data structures or algorithms. This permits the later modification of data structures without altering higher level procedures.

If one wishes to develop a computer implementation of the model, the issues of data structure and computational complexity must be considered. This may involve compromises in the areas of model soundness and completeness by restricting the types of queries and data objects permitted. In addition, the generality of some relations may be sacrificed for algorithm efficiency. Despite these significant problems, it is the author's belief that developing a model using abstract data structures has great potential.

Conclusions

The combination of shape algebras and symbolic logic can be a powerful tool in the specification of design grammars. A model of shape and spatial relations based on first principles of geometry, topology and logic improves upon previous efforts in several ways. Firstly, shape algebra representations are superior to those of more traditional 'kit-of-parts' systems in that they require minimal predetermination of structure and support direct manipulation of emergent features. Secondly, the use of logic provides a precise, generalized parameterization schema for shapes and spatial relations of any dimension and description. Thirdly, the construction of spatial relations by building high level relations and operations natural to design from primitive geometric ones appears to be an intuitive way of development. Finally, the use of a logic formulation allows one to focus on high level knowledge, not on low level data structures and implementations. These formulations are amenable to computer implementation.

By concentrating on the knowledge to be modeled and not directly on implementation, more powerful models of design can be developed. The potential for implementing these models with little sacrifice in functionality appears to be great. It is hoped that future research will adopt this approach and overcome the traditional bias of favoring implementation at the cost of representation.

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