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The Computability of Architectural Knowledge

Robert Oxman and Rivka Oxman

Faculty of Architecture and Town Planning
Technion: Israel Institute of Technology

A Theory of Design Knowledge for Design Computing

In an important contribution to the theoretical foundation of design computing, Mitchell noted "an increasingly urgent need to establish a demonstrably sound, comprehensive, rigorously formalized theoretical foundation upon which to base practical software development efforts" (Mitchell, 1986). In this paper we propose such a theoretical framework. A basic assumption of this work is that the advancement of design computing is dependent upon the emergence of a rigorous formulation of knowledge in design. We present a model of knowledge in architectural design which suggests a promising conceptual basis for dealing with knowledge in computer-aided design systems.

We require models which can represent the formal knowledge and manipulative operations of the designer in all of their complexity-that is formal models rather than just geometric models. Shape Grammars (Stiny,198O) represent an example of such models, and constitute a relatively high level of design knowledge as compared to, for example, use of symmetry operations to generate simple formal configurations. Building upon an understanding of the classes of design knowledge as the conceptual basis for formal modeling systems may contribute a new realization of the potential of the medium for design. This will require a comprehensive approach to the definition of architectural and design knowledge. We consider here the implications of a well-defined body of architectural and design knowledge for design education and the potential mutual interaction-in a knowledge-rich environment-of design learning and CAAD earning.

The computational factors connected with the representation of design knowledge and its integration in design systems are among the key problems of CAAD. Mitchell's model of knowledge in design incorporates formal knowledge in a comprehensive, multi-level, hierarchical structure in which types of knowledge are correlated with computational concepts. In the main focus of this paper we present a structured, multi-level model of design knowledge which we discuss with respect to current architectural theoretical considerations. Finally, we analyze the computational and educational relevance of such models.

Architectural Knowledge and Design Knowledge

We propose a working definition of the terms architectural knowledge and design knowledge and a discussion of these terms from an architectural theoretical point of view. Architectural knowledge may be considered a category of formal knowledge. It is the knowledge of architectural and urban form and constitutes the disciplinary core of knowledge within a larger body of professional knowledge. Architectural knowledge occupies a dominant role in design, and the acquisition of architectural knowledge may be considered one of the objectives of design education. Design knowledge manifests itself in the selection, manipulation, modification and adaptation of architectural knowledge in design. It provides the basis for integration of a disciplinary core of object descriptions with procedural, heuristic, causal and interpretive knowledge in characteristic procedures of design. The definition and formalization of both of these bodies of knowledge is a significant part of the effort to establish a theoretical foundation for CAAD.

It may well be that a limiting factor in the computation of design is not deficiency in CAD theory, but the lack of such formalized knowledge in architecture. Silvetti has described the problem of the schism caused by modernist theory's radical discontinuity and rejection of the authority of historical precedent and tradition as sources of professional knowledge (Silvetti , 1980). The current recourse to historical sources may, in a positive sense, represent a new epistemology in which an atemporal and styleless recourse to precedent becomes a means to reestablish the disciplinary basis of architectural knowledge (Hancock, i986).

The revitalization and definition of this body of architectural knowledge has been one of the leitmotifs of European theories for the past twenty years. This effort, including the formalization of knowledge of both architectural and urban form, has been principally associated with the European Neo-Rationalists, but may now he considered a general phenomenon. Among examples of this incipient body of knowledge are typological analyses and urban form studies (Gregotti, 1985) which attempt to define the elements and fundamental processes of architectural and urban design. Of further note is the resurgence of interest in composition, a subject of methodological significance until discredited as formalist and superseded by the concept of organization
There is a strongly revived interest in theory of composition (the formal and

spatial principles underlying the generation of form), and in formal analysis as a basis for identifying these principles.

Why are these developments of significance to the computation of design? In what was a relatively early theoretical statement regarding the role of a priori knowledge in design, Colquhoun suggested that the typified knowledge of prior solutions was an essential ingredient in architectural design (Colquhoun, 1969). This in contradistinction to the Functionalist emphasis upon the spatio-temporal uniqueness of each architectural problem. In the terms of our discussion, he and others since have established the integral relationship between architectural knowledge and design knowledge. It is a goal of this paper to elucidate the current rich state of architectural knowledge and its implications for design computing. As this knowledge becomes well-formulated and rigorously formalized, we can anticipate its use as a foundation for a new generation of knowledge-based CAAD systems.

A Computable Model of Design Knowledge

We describe a model of integrated architectural and design knowledge comprised of four levels. Declarative and procedural knowledge is seen as integral and linked within each level. The levels are:

Syntactic and formal elements and operations
    Elemental knowledge of architectural objects, object relationships, and operations on objects
Syntactic structures and compositional operations.
    Structuring of architectural elements and operations
Generic knowledge structures
    Highly structured generic knowledge organized typologically
Design paradigms and schemata
    Meta-knowledge and control knowledge for lower levels

These categories of design knowledge reflect significant subjects of current architectural thinking. As we shall see, compositional and generic knowledge forms have also begun to prove their relevance to design computing. The categories appear to be a convenient classification of knowledge with the potential for the integration of these levels in design systems. We believe that there also may be cognitive relevance to the model and that, in design, knowledge flows are reciprocally both top-down and bottom-up, within some framework such as chunked knowledge in networks (Newell and Simon, 1972).

How the idea of a structure of knowledge actually operates in design is a subject of some complexity. For the present argument, the implications of the concept of structured knowledge suggest certain interesting possibilities for operative characteristics in design systems. For example, should it be possible to move flexibly between levels, from a language to its modification schema, and to lower-level formal operations ? Design may, in fact, be conceived of as a structured, and often stylized, path through knowledge structures. Design learning may be conceived as the building of such knowledge structures; and the beginning of the learning process is characterized by for the absence of such a preform of knowledge structure.

In the following section we consider successively the various levels of a structured, multi-level model of design knowledge and the computational concepts which are related to the content of each level. In the final section, we return to the question of structure in knowledge and its relationship to computation, learning and education.

A Structured Multi-level Model of Design Knowledge

Elements and Operations in Architecture

Is it possible to establish a basic level of architectural formal object descriptions which goes beyond a finite set of discrete geometric primitives- that is, an elemental and pre-compositional level of knowledge which is above the geometric and the morphological and which is uniquely architectural? We can distinguish between two classes of formal knowledge in architecture included within this level. The first of these is a general category of knowledge of object descriptions which defines architectural formal categories. This is elucidated through formal analysis The second is a sub-class of syntactic knowledge providing operative knowledge in design of object classes, object to object relationships, and operations on architectural objects. This is elucidated through syntactic analysis. We refer to this knowledge collectively as formal knowledge.

There is an emergent body of knowledge of categories of form. This derives from diverse sources which may be generally described as formal analyses. Such formal categories are historically unique in the sense that they are not directly derivative of the formal categories of a historical tradition, such as the formal syntax of the Classical (Tzonis and LeFaivre,1986). Design theoretical work such as that of Baker (Baker, 1984, 1987), though not rigorous in the scientific sense, begins to establish categories of architectural form relating to such characteristics as volumetric organization, circulation patterns, axes, and boundaries. A modern approach to formal analysis in architecture began to emerge in Rowes work (Rowe,1947). This has since been developed by both researchers as well as design theoreticians such as Eisenman, whose early works emphasized the specification of categories of form and operations on form in integrated design analysis and synthesis (Eisenman, 1987). These efforts collectively begin to establish a vocabulary of form and formal relationships in architecture.

Syntax is the rigorous definition of these formal *categories in* an operative sense. Syntactic analysis helps us to define and classify syntactic elements and operations in *architecture. Higher* levels of syntactic knowledge include intermediate abstractions as media for structuring relationships in architecture, and transformational processes as operations on sets of objects. Shape Grammars provide a method for syntactic analysis as well as a formalism for *representing the* knowledge. The elements of syntax function both in the analysis and synthesis of designs, and in the work of Stiny as in that of Eisenman and others there is no abrupt transition between analysis and synthesis. Contemporary formal analysis may be *seen to* he contributing to a new architectural *epistemology, a* reformalization of architectural knowledge beyond tradition. However, we still lack a general, comprehensive theory of formal objects and operations in *architecture. Once* such theory becomes a rigorous body of knowledge, it may provide a foundation *level in* CAAD systems for formal processing. Like contemporary computer drafting systems, such systems would provide a *predetermined range* of object categories and relationships as the basis for construction of architectural objects.

With respect to a basic level of syntactic operations in design, existing CAAD systems are already very sophisticated in the provision of formal operations. Various kinds of symmetry operations, figure-ground, and layering are common *features, and* parametric transformations of elements can be developed (Mitchell, Liggett, Kvan, 1987). The questions *related to* the operational capacity of formal manipulative systems again seems not so much a CAAD problem as one of the formalization of architectural knowledge. What operations do architects require in their processing of architectural form ? We may develop a classification of procedures of architectural syntactic operations in various ways. Configurative operations are additive operations, including Boolean operations, which construct form from geometric elements. Stinys analysis of the Froebel gifts is a good example of an approach to classifying configurative procedures (Stiny, 1980). Another type of classification system might *derive from* the analysis of operations undertaken by professionals in the construction of traditional complex architectural representations, such as the *elevation H*abraken has such an approach in Form Writing (Habraken,l983). He attempts to define the basic operations for combining, substituting, modifying and transforming object to object relationships at a pre-compositional *level. Current* architectural interest in shearing, partial forms, strip relationships, scaling, layering, superpositions and other transformations suggest the potential richness of an architectural, as compared to computational, establishment of categories of operations.

An additional problem exists-that of the computational representation of forms. New operations demand new internal representations. Syntactic operations should be represented in an architectural computing system as forms of architectural knowledge. At this level, emergent forms, created by such operations as overlapping (Stiny, 1982) should be capable of flexible detachment through editing mechanisms not a minor computational problem. But the goal of providing such flexible editing tools is inherent in the idea of formal processing and we must be able to solve the computational problems involved. This necessitates specifying the repertoire of form processing procedures in architecture as both the conceptual basis and content of formal modeling systems. It is necessary to transcend the purely configurative operations of CAD systems in order to achieve true formal processing. To figure may he as significant in architectural design as to configure.

Syntactic Structures and Compositional Operations

This level of knowledge includes the properties of structure of sets of objects and the operative knowledge of nested operations. These structures and the ordering of operations into nested procedures may be represented in the computer as complex sequences of architectural syntactic operations. This is traditionally referred to as knowledge of composition. Composition is the establishment of formal relationships between the elements of architecture. Organization, a complementary concept, is the formation of relationships between the functional, circulatory and spatial elements of architecture. Composition is generally the formal disposition of elements relative to a referential system. Therefore, composition is traditionally, as well as computationally, the result of higher level entities employed in defining relationships between formal vocabulary elements. We can describe the elements, the processes for establishing the relationships relative to an underlying structure, and kinds of variations and transformations possible. Composition is also seen as possessing a unifying coherence derived from the superposition of a unitary ordering structure such as a grid, axial system, or modular system. Design may also be seen as a rule-based inflection of the ordering system. The ordering system may be an internal, underlying abstraction as in Classical building, or it may be realized and observable in the physical fabric of the building. These concepts underlie important descriptive work, such as the description of bodies of architectural work by menas of shape grammars, in which configurative relationships, or instances of differentiation and refinement within unitary structures, are described procedurally.

Now let us consider some contemporary work in which the aggregative and differentiative logic of an underlying unitary structure may be inadequate for description and representation. Libeskind has described !a changed consciousness about the making of architecture (Libeskind, 1984). In place of the classical concepts of order and coherence, we find a new sense of ordering which denies pre-established coherence. Eisenman, Tschumi and others have emphasized that the analysis of complex formal operations in composition is integrally related to design generation (Eisenman, 1984; Tschumi,1988). Transformational orders of design are established mainly through analytical procedures which become formalized as compositional strategies.

What is significant is that these theoretical developments pose a challenge to the unitary logic underlying both our ideas of composition and, by implication, to the associated conceptual basis of computer-aided design. This defines a shift, characteristic of an important body of design thinking, away from the idea of a unitary order underlying composition. A new compositional paradigm is emerging which is syntactic, transformational, and non-unitary (Whiteman, 1986). In this new compositional logic, there are multiple orders or no apparent order. Composition strategies include complex sequences of transformations such as shifting, shearing and cropping. There is a new composition which is, in spirit, related to the Modernist techniques of montage and collage. In place of the classical grid, contemporary orders are compound, twisted, sheared, shifted, fragmented and superimposed. An example is Meier's Crafts Museum in Frankfurt in which, within an underlying syntactic order of great complexity, both figurative and configurative strategies are employed in the generation of the composition. We are beginning to see attempts to classify the strategies of this new mode of composition. Architecturally, this may also involve a new representational paradigm (Whiteman,1987). The objects of design representations are frequently the series of successive states of a compositional transformation. The intermediate states of transformational procedures, are represented, and also, materialized in the design.

What is relevant in the context of our analysis is that it seems to contradict some of the current theory and practice of CAAD. The representation of architectural and urban form by geometric primitives and regular ordering systems, by parametric variations and geometric transformations is challenged by the richness of contemporary composition. Much work is required in order to define, formalize, and represent this vocabulary of structures and compositional strategies. We require other means of representation and a new computational

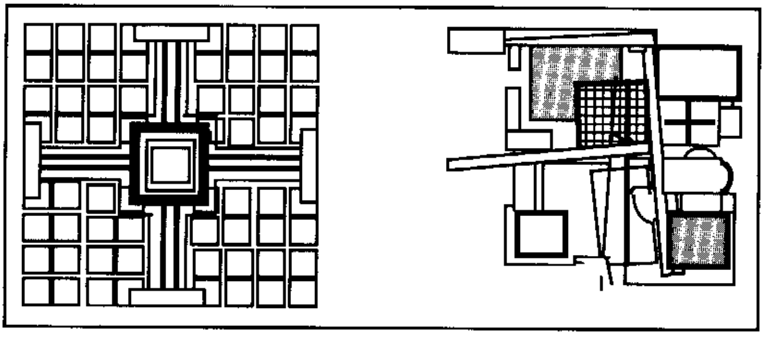

Figure 1 Unitary structure and complex compositional structure

approach for dealing with the classes of formal manipulations that are involved. There is beginning to be a recognition of the computational significance of these design-theoretical developments, and of the computational problems such as the need for dynamic editing!! (McCullough, 1988) in order to loosen the graphic gestalt in situations of emerging form. Obviously the idea of a new liberty in the computational capability of computer graphics systems is one of the challenging goals of software development.

Archetype, Type, Prototype

The generalization of typological knowledge from experience is one of the characteristic processes of design (Rowe, 1987). Architectural traditions may define relevant knowledge in the form of relevant types of problems and solutions, for example in the case of the Ecole des Beaux Arts. We will employ the term precedent, to describe such forms of higher-level generic knowledge. One of the major efforts of the current generation of architectural theoreticians has been to re-validate the precedent as a fundamental source of architectural knowledge without recourse to historic stylistic justification. Precedent becomes a form of atemporal generic architectural knowledge. This interpretation of precedent differs from the idea of canonic exemplars. The precedent is a generalized encoding of characteristic solution modes emphasizing the salient morphological characteristics. Here we encounter an extremely rich body of architectural knowledge in an incipient state of formalization. Within the scope of this paper, we can only suggest the theoretical and computational significance of these concepts.

The focal concept is that of the type and of knowledge generated through typological analysis. There exists a large body of literature on typological

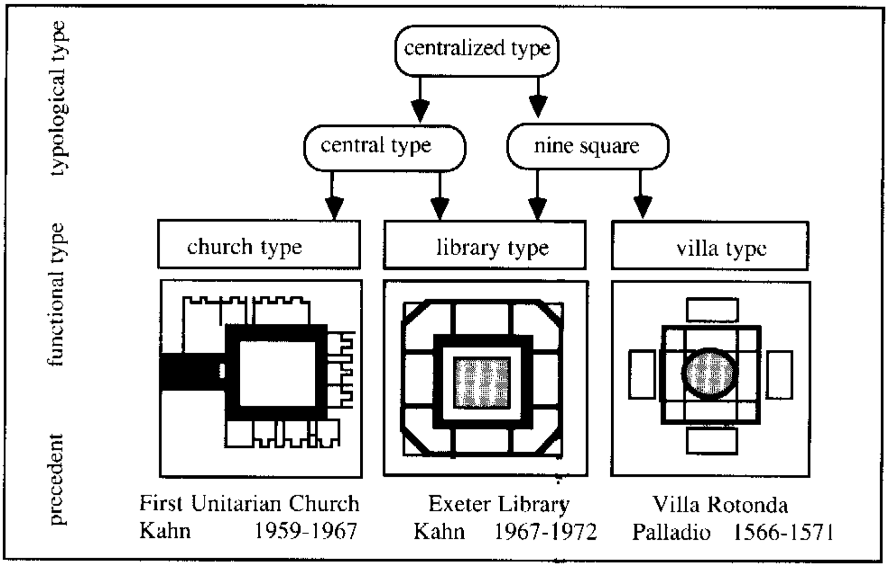

Figure 2 Precedents, functional types, high level typological concepts

analysis of both urban and architectural form. For Hancock, the type derives from 'culturally rooted form-function analogies" (Hancock, 1986). The typological distillation of essences from building morphology through synchronic historical analysis has established a rich body of architectural knowledge. Archetypes are the expression of such essences with the connotation of basic, recurrent type-forms and underlying morphological diagrams, such as the nine-square plan type. Generalization and typification process may typify the function or the context (situation) as well as the objects of design. All of this is encapsulated in the term type-the encoding of the salient features of a design object in a form which permits its application in current designs with modifications and variations. A good introduction to the term and its history can be found in Moneo (1978).

In types, we have a complex body of knowledge which includes the characteristics of the type, associated knowledge of procedures for the modification and refinement of the type, as well as semantic control of these procedures. This grammar of the type includes such knowledge as design heuristics, procedures for variations, and knowledge of the key design variables and their main states. As in formal languages, configurative steps for describing and modifying a type can be described as a rule system. Formal generation may be related to instances of a type as particular sets of syntactic

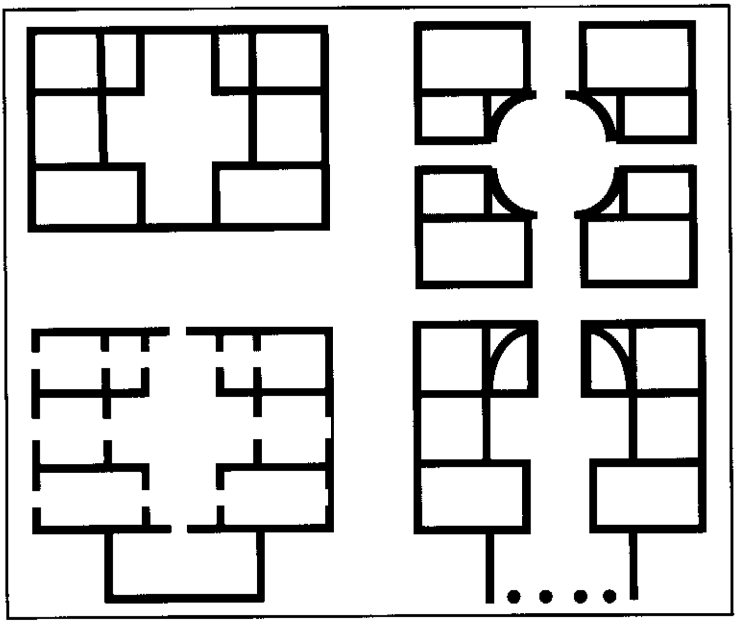

Figure 3 Refinement and adaptation of the prototype

rule chains. From a computational point of view, the major achievements in the representation of this level and its implementation in design systems has been in the area of formal languages and knowledge-based systems.

The prototype is a relatively recent computer concept for encoding the salient characteristics of the type, its refinement schema and some semantic basis for control of the refinement, modification and adaptation of the prototype (Gero, 1987; Oxman and Gero, 1988). In knowledge-based systems prototype schemata can be represented by such structures as frames. Such prototype schemata can then be incorporated in design systems (Oxman and Gero, 1987). These concepts provide a way to encode architectural and design knowledge in CAD systems. The prototype is a concept rich in potential for supporting top-down recursive refinement. Particularly promising is the ability to represent nested concepts in typological structures of knowledge. Given the generative capability of grammars, and the reasoning capabilities of knowledge based systems, their integration in future prototype based design systems is most promising (Oxman, 1989).

Paradigms and Schemata

Paradigms and schemata are highly structured networks of knowledge. Design knowledge becomes paradigmatic when the types are general types or general problem classes rather than specific building types. Paradigmatic knowledge is a form of higher-level knowledge which derives from a class of architectural problems and is relevant to all members of the class regardless of the particular building type. Knowledge of the heuristics of all problem types in which the basic generative functional elements are repetitive, such as the dwelling and the dormitory, is such a paradigmatic class.

Paradigmatic knowledge is holistic, high level knowledge of problem classes. This is meta-knowledge in which the concept of class may contain a common philosophy which identifies relevant problems of the class, their characteristics, appropriate methods, definition of goals,etc. Functionalism might be considered such a design paradigm carrying associated value systems as part of the knowledge of the paradigm. Little work has been done on the formalization of paradigmatic knowledge. The incorporation of meta-knowledge in design systems has been experimented with in knowledge-based systems. This level of knowledge provides the linkage back in the chain of paradigms, precedents, compositional strategies, and formal elements and operations.

The Design and Computational Significance of the Multi-Level Model

It is our assumption that knowledge in design is structured and that there is a meaningful relationship between levels, or types of knowledge. There appears to be a significant cognitive role of generic structures of knowledge in controlling syntactic operations at lower levels in design. That is, typological knowledge provides not only a classification system, but the generic classes of usage of complex syntactical operations. It is a generic source of syntactical operations, that is, the experienced designer knows how to operate differently on different classes of plans. We should be able to represent and encode such multi-level knowledge in a computer system (Oxman, 1989).

A multi-level model of design knowledge has significant potential implications for the operating characteristics of design systems. Future design systems may integrate these levels and permit both top-down and bottom-up operation. Ultimately such systems, must go beyond the simple provision of an enhanced capacity for formal manipulation. They must also integrate both interpretive knowledge as well as causal knowledge in the form of algorithms.

We can identify three important classes of research which are necessary for the realization of integrated design systems with enhanced formal processing capacity. The first is the formalization, representation and encoding of architectural and design knowledge for both two-dimensional and three-dimensional modeling in a manner which solves the computer graphics problems, such as those of emergent form. We require further experimentation and development of multi-level systems (Mitchell, Liggett, Tan, 1989) of multi-mode operation in design systems (Oxman and Gero, 1987), and with integrating algorithmic computation with knowledge-based reasoning. Knowledge-based systems appear to provide important potential as knowledge-integrators in design systems.

Conclusions

Design Knowledge: the Educational Implications

Such a structured model of design knowledge would appear to have an important relationship to a theory of design learning. We have already mentioned our supposition that knowledge acquisition and design memory are probably related to the concept of structured knowledge. This is generally supported by current research in Al and cognition (Galambos, Abelson, 1988). Design learning involves the generalization and classification of the salient aspects of design experience (or design teaching) according to some existing schemata of knowledge. The acquisition and modification of design experience is dependent upon the schema. Knowledge of the solution space enables the experienced designer to efficiently define current problems. In young students, lacking such pre-structures of knowledge, it is increasingly important to convey well-formalized design knowledge. We might postulate that for early design education it would be preferable to inculcate the structure of knowledge, the principles, rather than the detailed content of specific chunks. The model of design knowledge which we have suggested, with its emphasis on formal and procedural knowledge, might become the explicit content of design education.

The Relevance of CAAD Education for Design Education

This paper has attempted to demonstrate the important linkage between architectural theories and the computerization of design. We would now like to argue that CAAD education has relevance as a medium of design education. This has been demonstrated by a generation of educational experience in CAAD. Design learning requires the abilities to formalize and to generalize design experience. Dealing explicitly with the formalization of design knowledge is one way of improving design teaching. Encoding architectural knowledge for CAAD and programming can help the designer-user understand

and use this knowledge more effectively in design. Mitchell has spoken of the 'computer-trained imagination (Mitchell, 1984). Teaching architectural knowledge as computational principles and encountering design knowledge through the electronic processing of architectural formal content is an important medium for teaching design principles (Oxman,Radford, Oxman,1987). *There appears* to be rich potential for the integration of modalities between design teaching and design computation.

The Medium and the Designed Artifact

The computation of designs is dependent upon the underlying systems of conception, representation and notation of architectural form which are implicitly *reflected in* the conceptual schemata of CAAD systems. Perhaps the converse may also be true, and the medium may demonstrate its potential as a creative way of designing. Here a theory of design for computers begins to *emerge as* a computational theory of design. We have briefly reviewed the changes in the conception and vocabulary of architectural and design knowledge. Much work on the formalization of this knowledge is *necessary, as is research into* the internal representations which *are* required to represent *compositional structure in* design systems. As *there is* creative potential for *these new* representational systems in design, so there is in design computing. If design computing should *become responsive to* the importance of the concept of formal modeling, then computers as interactive knowledge processors may be capable of becoming truly capable partners in design.

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