Objects, Properties and Relations

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Abstract. The paper takes a fundamental look at the composition of digital design representations, in particular at the objects they comprise, the properties of these objects and relations between objects. It proposes that the clarity of domain principles underlying such representation should be matched by explicit, flexible implementations that not only fit design actions and transactions rather than institutional classifications and prescriptive views of architectural information but also challenge formulations of the domain principles.

Keywords: Representation; symbols; relations; constraints.

CAAD representations

Digital representations of architectural designs generally consist of graphic objects related to each other implicitly (e.g. through similarity or position) or explicitly (usually by means of attached constraints). The adoption of vector graphics as basis for CAD has meant that digital representations moved away from analogue ones (whose structure is more akin to raster graphics) towards the geometric means of architectural projection (Evans, 1995). This opened up possibilities for precise and accurate geometric descriptions of architectural form and the consequent exploration of geometries yet unaccustomed in the built environment. At the same time, it promoted a troublesome confusion between the symbols of a representation (i.e. meaningful design entities such as a column) and the mechanisms used for their implementation (e.g. the line segments that combine to describe the footprint of the column in a floor plan). It also gave rise to a version of the imagery debate, where descriptive representations (drawings) were often vilified as anachronistic obstacles to computational design and the development of scientific propositional representations (Bijl, 1982; Gero, 1986; Kosslyn, 1994).

The debate ended even more abruptly than in cognitive science with the popularization of the computer in the 1990s and the subsequent widespread realization that CAD offered unprecedented support for geometric modelling, leaving CAAD split between direct applications of commercial software and representational formalisms developed specifically for the architectural domain. The problem intensified with the recent emphasis on modelling techniques like BIM that derive jointly from propositional principles and ideas on information standardization. These promise a performance similar to that of domain formalisms but on the basis of institutional classifications and pragmatic, professional considerations rather than basic principles (as the dual graph representation) or computational analyses of particular corpora (like in shape grammars).

The present paper takes a fundamental look at the elementary components of CAAD representations
from a combined semantic / syntactical point of view, with the main focus on the significance and interpretation of descriptive primitives and their combinations. This point of view relates to representational attempts from within CAAD, as the definition of relevant objects, their properties and relations has been among the main subjects since the founding period of the area. It also responds to requirements from architectural practice – of the kind that become apparent in advanced use, once the euphoria of new possibilities is partly replaced by frustrations stemming from limitations, redundancy and intensity of labour.

Early CAAD representations attempted to overcome the limitations of the then primarily alphanumeric computer but at the same time linked to domain knowledge, especially principles of architectural composition. As a result, they placed emphasis on spatial aspects, usually making use of explicit spatial primitives, for example as descriptions of states in a generative process, while relations between them often remained implicit, e.g. in the generative rules of a shape grammar. A notable exception was the dual graph representation with its adjacency and access graphs (Steadman, 1983). Also important have been attempts to implement space representations in a manner dissimilar to solid building objects, attempts that extended to design interaction (Kurmann, Elte and Engeli, 1997; Yessios, 1987). Such approaches and their results deserve renewed attention in the framework of recent developments (e.g. BIM, interoperability, parameterization), which raise the level of specification in a representation by posing questions of relevance (e.g. what is the meaning of a geometric manipulation as a design action), as well as by being quite sensitive to matters of complexity, completeness and consistency.

The starting point is a neutral definition that generalizes existing approaches: a representation is a formal system for making explicit certain aspects of a particular class of entities. The product of applying this representation to a specific entity is a description. A symbolic representation of the kind used in CAAD consists of:
- A set of symbols representing salient properties, parts etc.
- A rule system that connects these symbols to the aspects and entities to be described.

For example, Arabic decimal numbers have the following symbol set

\[ S = \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9\} \] (1)

and use positional notation with 10 as the base to arrive at descriptions:

\[ n_n \cdot 10^n + n_{n-1} \cdot 10^{n-1} + \ldots + n_1 \cdot 10^1 + n_0 \cdot 10^0 \Rightarrow n_n n_{n-1} \ldots n_1 n_0 \] (2)

A well-defined representation not only produces unambiguous descriptions, it also affords transformations that extend applicability. Binary numbers, for instance, follow the same structure as above, only the base changes from 10 to 2 and the symbol set is accordingly reduced:

\[ S = \{0, 1\} \] (3)

\[ n_n \cdot 2^n + n_{n-1} \cdot 2^{n-1} + \ldots + n_1 \cdot 2^1 + n_0 \cdot 2^0 \Rightarrow n_n n_{n-1} \ldots n_1 n_0 \] (4)

This definition makes evident that representations are partial and complementary, each suited to a particular task or context. Decimal numbers are arguably handy for humans, binary numbers can be mapped onto the two states of a switch and are therefore appropriate for machines, while representations like \[ \text{|||} \text{|||} \text{||} \text{||} \text{||} \] are better than either decimal or binary numbers for counting with analogue media.

It follows that the search for appropriate descriptive primitives is by no means trivial. Identifying primitives that serve different purposes is a critical issue but we should also expect that most representations relate to others in an unambiguous manner that permits direct and reliable transformation of one description into another. Moving effortlessly
from one representation to another is one of the cognitive characteristics of humans and we should demand that similar intelligence and coherence becomes a basic quality of our digital tools.

**Objects: solids and voids**

From a design point of view the dual networks of building elements (‘solids’) and spaces (‘voids’) form an obvious departure in a search for primitives, as they form the basis of conventional analogue representations like floor plans that have been serving us well for a long time. This on the one hand means that we are quite familiar with such primitives and on the other suggests that there is a strong correspondence between the primitives and primary design concerns. Despite the variation in form, which arguably makes impossible the derivation of a precise, finite symbol set as in the previous examples, these two main categories provide us with extensive repertories of descriptive primitives for most aspects of architectural design. These repertories are obtained by classifying building elements and spaces by their geometry, function or use. The results within a particular sub domain are generally compact sets, as demonstrated in shape grammars.

As these symbols are linked to a building through direct mapping based on descriptive geometry, the representation exhibits properties derived from the real world. Taken together all spaces and building elements in a building fully occupy the area and volume of the building without overlaps or empty parts. If we consider each space and building element to be a single, integral entity in the representation, this opens up interesting possibilities for parsing the representation into additive and subtractive configurations that provide unambiguous descriptions that nevertheless may abstract and defer parts and aspects of the design. For example, if the spaces and openings of a design are known, we may safely assume that the remaining space within the outline of the building is occupied by building elements. Even if there are no decisions made on the load-bearing structure, thermal insulation or materials of the missing elements, the picture that emerges is sufficient for making educated guesses.

Such abstraction possibilities are enhanced by transfigurations that relax mapping constraints, for example through the derivation of topological representations that focus on the existence of certain objects and relations. These describe a design by means of graphs where vertices normally represent objects and edges relations between them. Interestingly, this can be reversed as in the building graph,
where corners and other junctions are described by
vertices while building elements are the edges be-
tween them. This not only preserves visual similar-
ity with conventional representations like the floor
plan but also accentuate aspects of complexity that
are otherwise only implicit, with detrimental effects
to the quality of e.g. cost estimations. Similarly, an
access graph makes explicit aspects pertaining to
circulation at a higher level of abstraction that can
nevertheless be directly translated into geometric
information (e.g. paths).

An important corollary of such representations is
the use of mathematical expressions for the formal
description and measurement of familiar yet vague
concepts (especially in early design). For example,
the degree (valency) of a vertex is a reliable indica-
tion of complexity. In an access graph a high vertex
degree indicates a space possibly traversed by a
large number of pedestrian routes, while in a build-
ing graph it points out structurally complex details.
Such expressions and indications are of particular
value for the analysis and abstraction of complex de-
scriptions, e.g. in the framework of typological inves-
tigations (Steijns and Koutamanis, 2006).

The treatment of symbols for building elements
and spaces in designing reveals fundamental dif-
fences in the way we approach these two basic
categories. Building elements, being the implemen-
tation entities of the building, form focal points for
design and communication, where integration of
aspects seems to take place. By contrast, spaces (i.e.
what is bounded by the building elements) remain
relatively passive containers of static information,
including output from operations on building ele-
ments (e.g. thermal insulation calculations), even
though what they contain is arguably the main tar-
get of architectural design and certainly the starting
point for operations on building elements (i.e. per-
formance requirements on the basis of activities to
be accommodated).

The main problem of defining and using such
symbols lies in the shift from descriptive representa-
tions to propositional ones. A common problem with
many systems that stress the propositional dimen-
sion (e.g. information and interoperability standards
or models) is the weakening of geometric (and con-
sequently spatial) information. This feeds back to the
definition of the entities and their symbols, caus-
ing an uneasiness that becomes evident at critical
points, e.g. transitions between abstraction levels.
Building elements are often represented and treated
as vague aggregates whose subdivision owes less to
structural than perceptual principles like transver-
sality and collinearity (Koutamanis, 2007). Relations
between the relatively vague building elements and
the more specific building components out of which
they are constructed remains a technical and con-
ceptual challenge that cannot be solved by means of
techniques based on technical drawing.
Spaces are even more problematic in representation. Initially only implicit in CAD models they are either derived from the bounding elements or naively represented by surfaces and solid objects – a technique focusing on the interpretation of emptiness and requiring mental reversal to recognize the convex form in concave objects. While there is wide interest in the articulation of building elements and the way they are composed out of building components, subdivision of spaces into parts and zones attracts little interest and is generally reduced to vague indications by means of furnishings, as in analogue drawing.

The acceptance of the dual network of spaces and building elements as a basic level of architectural representation should not prohibit the development of alternative bases and elaborations that serve additional purposes. For instance, the recognition-by-components theory provides a coherent framework for the recognition of architectural scenes that is quite compatible with architectural conventions (Biederman, 1987; Koutamanis, 1997). Adding this framework to architectural representation offers possibilities for perceptual and cognitive aspects like aesthetics. Such additions can also be instrumental for making effective distinctions between the representation objects and the means or references used for the definition of specific aspects, such as between the complex surfaces used for defining the form of a shell defined and the shell form itself.

**Properties**

Representations are meant to make things explicit. In practical terms this means that the implementation mechanisms used for each symbol should facilitate identification and measurement of properties of the symbolized entities. In first instance this refers to geometric properties like the perimeter, area and volume of a space or building element. An effective and reliable correspondence between representation symbols and implementation mechanisms permits not only straightforward measurement of such properties for the analysis and evaluation of a design but also direct and meaningful manipulation of the representation so as to modify such properties in the framework of design actions.

A second type of properties concerns non-geometric aspects. These may derive from external categorizations, such as catalogues of building components and interoperability standards that support communication or even historical and morphological systems that constrain interpretation of form. Such properties are usually attached to objects in the representation as labels which may underlie the organization of the document accommodating
the representation (e.g. layers in a CAD system) or provide links to external databases. Labels may also refer to performance specifications, of the kind normally collected in a brief. The presence of these in a representation facilitates analysis and evaluation, from allowing elementary comparisons such as that between the area allocated to an activity and the one prescribed in the brief to providing input and criteria to simulations (in addition to the geometric information provided by the basic representation).

In many cases properties refer directly to specific parts of an object’s form, from integral parts such as corners to optional features like holes. While most parts are identifiable as discrete entities which belong to the object in an unambiguous manner, optional features must be linked to the object in a flexible manner that permits similar treatment, e.g. by means of constraints. Design actions and transactions frequently focus on particular features, not necessarily ignoring consequences for the rest but usually deferring resolution of emerging problems to a later stage (abstraction). This may run contrary to the underlying approach of a system, causing inconsistencies and conflicts that relate more to the means (the model) than the end (the design), raising once again the fundamental question of how we subdivide basic objects.

**Relations**
Implicitness in analogue representations also extends to relations between objects, making recognition of both objects and the ways they relate to each other a matter of human perception and interpretation. Keeping relations implicit is probably the last major analogue vestige in digital representations and a primary obstacle to the development of comprehensive design and information systems capable of e.g. fully simulating and analysing the behaviour and performance of buildings. Yet, attitudes towards making relations explicit in a design representation tend to be ambivalent due to the high cost of establishing and maintaining the resulting complex networks.

Describing and handling all relevant relations is a matter of intelligent techniques rather than brute force (Eggink, Gross and Do, 2001) but at a basic level most relations can be reduced to the elementary condition of adjacency: the mere positioning of two objects next to each other assumes a variety of architectural meanings, from access to a space and daylighting to positional or size tolerances and interfacing constraints. Very few of these are expressed explicitly, even in parameterization, despite their ability to express directly and succinctly complex issues like circulation intensity through the degree of a vertex in a topological representation. Adjacency-related bilateral constraints, most of which result from sequences of adjacency relations, form the basis of geometric parameterization, i.e. variations in the form or position of an object.

In addition to bilateral relations, design representations often contain structured representations of multilateral relations, e.g. grids. These are often treated as mere reference frameworks, usually geometrically fixed. However, they are more effective as abstractions of extensive three-dimensional structures. As such they provide efficient and transparent schemata for handling wider problems such as topological parameterization, i.e. variations in the composition of an assembly. The close links between geometric and topological parameterization often make the latter appear as a consequence of the former (e.g. in a staircase the number of steps usually follows the size of the steps) but the reverse is equally plausible (e.g. the sizes of steps can be determined on the basis of the possible number of treads in a specific spatial context).

Many relations refer to specific features or aspects of an object rather than the whole object. This is often evident in parameterization situations, where for instance only one of the three dimensions of an object or a single edge of an outline may be affected by a propagated change. Similarly, pedestrian connectivity between two spaces is based on their respective adjacency to opposite long sides of same door but only weakly to the width of the door.
(i.e. the size of these sides). Feature selectivity is even more pronounced in multilateral relations, e.g. those connecting the position of a concrete column relative to other members of the load-bearing structure with the size and form of the column and the rebar composition.

A reversal to the subdivision of objects mentioned earlier is the formation of larger assemblies and clusters, which derive mostly from multilateral relations. With building elements these tend to be rather clear, as in the formation of load-bearing grids out of beams, posts and their connections. Spatial assemblies may be more loosely defined, as they are often based on labels, e.g. the activities housed in a collection of spaces. Zoning is probably the most significant technique of clustering objects. The description of zones is frequently vague yet clearly focused on general salient features and parts like the facade of a building or a desired route and the colonnade that defines it. Zones are efficient mechanisms for describing the overall spatial structure of a design in a way that makes primary behaviour and performance issues transparent. This also applies to the subdivision of primary objects: internal zones can be employed to describe the internal articulation of spaces with a seemingly low complexity such as classrooms and office cells.

**Discussion: representation principles and open questions**

The clarity of the domain principles underlying structured representations can be misleading. Firstly, it attenuates the multiplicity of abstraction levels and aspects on which an architect operates for a given problem, moving rapidly back and forth on the basis of elliptic connections. Secondly, it stresses the integrity of basic entities like spaces and building elements at the cost of possibilities offered by further subdivision or abstraction. Thirdly, it reduces...
the urgency of making relations explicit: if they are so evident and (locally at least) manageable, we could allow designers to employ them at their discretion, as in the ad hoc networks of most parametric systems.

The highest priority for the development of such representations lies in the choice of appropriate implementation mechanisms. Stating that these should meet the requirements of describing design processes and products is no wishful thinking but the starting point for collecting definitions and clarifications like the ones attempted in this paper towards basic principles and focused research questions. The dual network of spaces and building elements is one of these principles, less as a universal truth and more as a convergence level where most design issues, aspects, actions and transactions can be encountered and connected to each other. The most important with this duality is the acceptance that neither network derives deterministically from the other. Instead, they complement each other in a heterarchical fashion that permits incompleteness and uncertainty in design.

At the level of individual objects, we have yet to develop comprehensive solutions for the direct correspondence between the geometry and the symbolization of an object. Transitions between design stages or abstraction levels reveal serious weaknesses in existing approaches. Accepting the vagueness of object demarcations and subdivisions is a first step in the direction of multi-level, fuzzy representations that match (and possibly enhance) the flexibility of design thinking. Linking these representations to object taxonomies is probably unavoidable but we should question institutional classifications and prescriptive approaches to design information, especially concerning their seemingly pragmatic underpinnings.

References