Graph-based models of space in architecture and cognitive science - a comparative analysis*

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Abstract

Graph-based operationalizations of space are used in architecture as well as in cognitive science. In such models, environments are usually described by means of nodes and edges, roughly corresponding to places and their spatial relations. In the field of cognitive science, view and place graphs are models of mental representations of environments and used for the explanation of wayfinding behavior such as exploration and route planning. In architecture, space syntax and visibility graph analysis aim at identifying and describing structural properties of built environments that determine their usage and experience.

In cognitive science, mental representations of space cannot be seen independently from the formal and configurational properties of the corresponding environments that are well captured by architectural description systems. Vice versa, formal descriptions of space as used in architecture gain plausibility and relevance by incorporating results from cognitive research that allow the prediction and explanation of actual human behavior. In this paper approaches from the two different disciplines are therefore reviewed and compared. Special interest concerns their scope, structure, and representational content. Parallels, differences, and specific strengths are discussed. Furthermore, based on recent empiric work, strategies to integrate aspects from both disciplines are outlined.

1 Introduction

In mathematics and computer science a graph is an abstract construct consisting of objects called nodes and their relations implemented in edges. Many real-world problems of practical interest can be efficiently represented using graphs as a flexible, extendable, and generic framework

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offering various straightforward algorithms for the solution of specific higher level questions. Both in architecture and cognitive science mathematical graphs are used to systematize the description of the human spatial environment. Despite this shared overall scope and formal approach, the two academic communities are widely unaware of each other and not familiar with the mutual concepts. An example of a collaboration of researchers from both disciplines is the investigation of navigation behavior in complex architectural indoor environments (Wiener & Franz, 2005; Franz & Wiener, 2005; Hölscher, Meilinger, Vrachliotis, Brösamle, & Knauff, 2005). During this interdisciplinary research it became clear that both disciplines can mutually benefit from each other. However, due to a different terminology and different approaches a general discussion of concepts appears necessary. In the next section, graph concepts from both disciplines are therefore reviewed synoptically. Particular interest concerns the purpose of the different approaches, the special features and usage, and the representational content. In Section 3 and 4 integrative concepts combining elements from both disciplines are outlined, hopefully providing a common basis for further fruitful interdisciplinary exchange.

2 Comparative analysis

2.1 Graphs in Spatial Cognition

General overview. In spatial cognition and artificial intelligence, graphs have been used as models for mental representations of environments for decades. For example, in 1979, Byrne suggested that the memory for urban environments is realized in a network of places (see also Kuipers, 1978). Ever since a multitude of such graph-like models of spatial memory have been developed (e.g., Leiser & Zilbershatz, 1989; Chown, Kaplan, & Kortenkamp, 1995). The graph concept serves several purposes in spatial cognition: First and most importantly, graphs are models of the mental representation of environments, serving as working hypotheses for the structure, format, and content of spatial memory which can be empirically tested. Furthermore, graphs can describe the set of movement actions available at a given place.

The particular appeal of graph structures as models for spatial memory arises from their increased flexibility as compared to map-like representations of space. For example, while basically being topological structures, by labeling or weighting single edges of graphs, distance and direction information is included that allow for metric navigation abilities such as short-cutting behavior (Hübner & Mallot, 2002). Additionally, various non-spatial information can be attached to the nodes, for example, places can be labeled with emotional or episodic information (Arbib & Lieblich, 1977). Also, in contrast to map-like representations, graph structures allow the representation of incomplete or inconsistent knowledge that appear necessary to explain several empirical findings in human spatial cognition (e.g., Mallot & Gillner, 2000). Taken together, due to their minimalism and effectiveness graph-like mental representations of space are ecologically plausible, sufficient for the explanation of behavior, and, last but not least, they fit well to the neural structure of our brains.

Occupancy grid. In artificial intelligence, occupancy grids are often used as representations of space for autonomous navigating robots. In occupancy grids the environment is mapped on a regular array of cells, which can be conceived as a specific graph implementation. Each cell is connected to its eight surrounding neighbors and holds a probability value that the cell is occupied by an obstacle (Moravec & Elfes, 1985). Occupancy grids do not represent selected places but are continuous representations. The advantages of these structures are their simplicity and their metric embeddedness. However, occupancy grids often suffer from their directional inhomogeneity and their general structural rigidity.

Place graph. In the place graph concept, nodes correspond to single places or positions within an environment, edges describe the connectivity between nodes. In their most basic form place graphs are parsimonious purely topological representations of space, in which nodes carry local position information, allowing the identification of the corresponding place. Edges carry local navigation rules, such as 'turn left' or 'follow road', that allow navigating between nodes. Kuipers (2000) and Kuipers, Tecuci, & Stankiewicz (2003) have suggested a slightly different concept. In this bi-partite graph both places and paths between places are represented as nodes that are linked together by edges. While both of these concepts are in their basic form topological representations of space, metrical information such as distance and direction might be associated. In contrast to occupancy grids, place graphs represent selected places or positions within the environment rather than the environment as a whole and can therefore be conceived as more sparse.

View graph. Schölkopf & Mallot (1995) have proposed a minimal spatial memory model in which each node corresponds to a pictorial snapshot of the environment as seen when navigating a given place transition. Nodes are connected by edges if the corresponding views can occur in immediate sequence while walking through the environment. They are labeled with local navigation rules. The basic idea of the view graph is to generalize route memories given as chains of recognition-triggered action sequences to a more flexible yet still parsimonious representation of space allowing for complex navigation behavior such as route planning. View graphs have been successfully used for robot navigation (Mallot, Franz, Schölkopf, & Bülthoff, 1997) and for the explanation of human navigation behavior (Gillner & Mallot, 1998; Steck & Mallot, 2000).

2.2 Graphs in architectural analysis

General overview. Graph applications in architecture are in a long tradition of graphical or diagrammatic analysis and have been substantially influenced by the phenomenal city descriptions of Lynch (1960). The need for strictly formalized description systems arose from the wish to do quantitative comparisons between spatial configurations in order to identify the essential properties in terms of function or usage. In this domain of *space syntax* analysis, spatial organization patterns were seen as close parallels to the underlying social structures (Hillier & Hanson, 1984; Hillier, 1996). Besides applied research, graph investigations in architecture particularly concentrated on methodological issues such as the transfer of analysis techniques on arbitrarily shaped environments or on variable scale levels and on the formalization and automation of the graph generation process. Also approaches to determine and minimize the number of necessary nodes were explored (Peponis, Wineman, Rashid, Kim, & Bafna, 1997).

Access graph. One line of research focused on inter-cultural comparisons as well as on the application in architectural practice and therefore pursued the elaboration of improved generic graph descriptor variables (e.g., capturing the connectivity, centrality, control level of places). Early space syntax analyses (Hillier & Hanson, 1984) made use of phenomenal spatial units such as clearly defined rooms or labeled places for their nodes, while graph edges binarily signified their mere connectivity. As additional graph element, the accesses to the individually analyzed spatial configurations were considered as root nodes of the so-called justified graphs.

Axial maps (Hillier, 1996) consist of nodes describing lines of sight or straight movement and their mere intersections as binary edges. They are based on a prior partitioning of the underlying environments into a near minimal set of convex subspaces. In a second step, these convex hedras are connected by the smallest possible number of straight lines of maximum length. The generated graph has to meet the requirement that each adjacency of the subspaces can be associated to at least one axial line. A recent extension of axial maps are angular maps that additionally consider the angle between the axes in the connectivity edges (Turner, 2001). Axial maps have been mainly used for the analysis of city quarters. Strong correlations between derived descriptor variables and statistical pedestrian dispersal have been found.

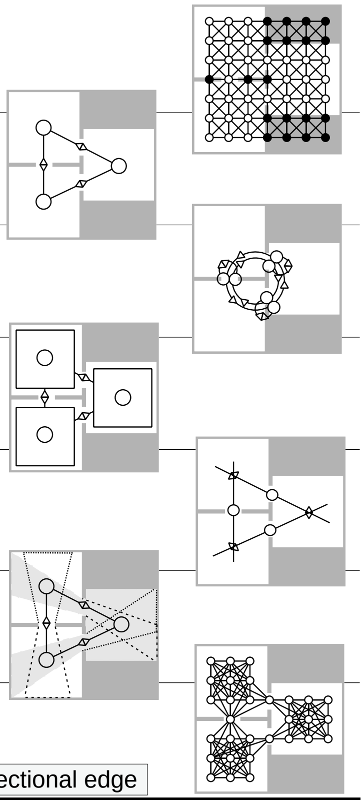
Isovist field. For analyzing spatial characteristics of smaller environments, Benedikt (1979) has proposed isovists as objectively determinable basic elements. Isovists are viewshed polygons that capture spatial properties by describing the visible area from a given observation point and therefore lend themselves particularly well for analyzing open-plan indoor spaces. In order to describe spatial characteristics of environments beyond a single sensory horizon, isovists can be used as content in graph nodes and connected by intervisibility edges (Turner & Penn, 1999).

Visibility graph. Derived from isovist fields, Turner, Doxa, O'Sullivan, & Penn (2001) have proposed visibility graphs as a promising way to optimize the computational graph analysis. Visibility graphs replace the isovist as node content by mere intervisibility information translated into edges to other nodes that are now distributed on a regular and dense occupancy grid of possible observation points. This technique facilitates the derivation of global or second-order measurands like for example on visual stability that may be relevant for locomotion and navigation. Indeed, recent empirical studies (e.g., Franz, von der Heyde, & Bülthoff, 2005; Wiener & Franz, 2005) have shown that visibility graphs are useful to predict spatial behavior and affective qualities of indoor spaces.

3 Synthesis

As apparent from the previous section, formally similar graph-like representations of space serve different purposes in spatial cognition and in architecture. While graphs in spatial cognition are mainly used as models for mental representations of environments, in architecture they are used as generic formalized description-systems for the structure and shape of built environments. However, despite these different perspectives, the concept of environment (i.e. the sum of behaviorally relevant aspects of an organism's habitat) as represented content is another fundamental communality between the disciplines implicating further parallels. The combination of general compatibility and independent directions of development makes integrative concepts appear as particularly promising: For example, mental representations of space as studied in cognitive science cannot be seen independently from the formal and configurational properties of the corresponding environments. Vice versa, formal descriptions of space as used in architecture gain plausibility and relevance by incorporating results from cognitive research. Below

graph model	nodes	edges	pictogram
occupancy grids	xy-intervalls with obstacle probability	predefined, non-directional	
place graph	local position information at places	local navigation rules	
view graph	local position information at place transitions	local navigation rules, directional	
access graph	spaces	connectivity	
axial map	lines of sight	intersections	
isovist field	viewshed polygon	mutual visibility	
visibility graph	xy-intervalls	mutual visibility	



○ = node ◁ = directional edge ◁▷ = non-directional edge

Table 1: Overview on the different graph models.

two scenarios are described that demonstrate how graph elements from each discipline can be integrated into models of the other.

Transfer from architecture to cognitive science. In cognitive science the analysis of navigation behavior plays a key role for the understanding of spatial abilities, spatial processes, and mental representations. For example, in route planning tasks the analysis of navigation behavior allows the inference of both route planning strategies and properties of the underlying representation of space (e.g., Wiener, Schnee, & Mallot, 2004). While navigation behavior in familiar environments probably mainly depends on the interplay of internal spatial representation and planning processes, spatial tasks in unfamiliar environments such as search and exploration are more likely to depend also on the directly perceived structure of the environment. Yet the structure of environments is captured only very coarsely by graph-like descriptions of space as used in the cognitive sciences. Relating navigation behavior to these coarse descriptions will therefore only reveal a part of the influence of environmental factors on behavior. However, relating navigation behavior also to more elaborated description systems of spatial form and structure as provided by architectural approaches (e.g., visibility graphs or isovist analysis) promises further insights into the mechanisms and strategies underlying human wayfinding behavior.

Transfer from cognitive science to architecture. Vice versa, also the discipline of architecture can benefit in various ways from graph related concepts developed in the cognitive science community. For example, the view graph demonstrates how to integrate pictorial information into graph representations. Views provide light and color information and could be used alternatively or complementary to isovists as node content in order to consider individual properties of places at a finer scale. Since various studies in environmental psychology have shown that light and color are primary factors for the experience of environments (e.g., Mehrabian & Russell, 1974; Küller, 2001), the architectural relevance of such properties is well arguable.

Furthermore, architectural graph applications may take advantage of findings of many experimental studies in spatial cognition. The general problem of a near optimal parsimonious use of graph nodes, for example, is also addressed in robotics (Franz, Schölkopf, Mallot, & Bülthoff, 1998) and in psychophysics (Gillner & Mallot, 1998) investigating the essential constituents of landmarks and decision points.

Finally, applied questions from architectural practice such as the comparison of design alternatives for large building complexes with respect to their navigability cannot consider the building structure independent from the human mind (e.g., Werner & Long, 2003). In order to allow accurate predictions of human behavior in specific cases (e.g., emergencies), both reasonable assertions on the mental representations as on likely strategies or heuristics underlying navigation behavior are required. Of course, here cognitive science cannot yet readily provide conclusive answers, however, a strong overlap of interests between both disciplines becomes clearly obvious.

4 Outlook - toward a generic analytic representation?

This paper has outlined several regions of common interest between graph applications in architecture and cognitive science beyond the purely formal. These communalities promise mutual benefit from a better awareness and knowledge of the concepts of each other. Although originating from two different perspectives and pursuing different goals, due to the common denominator environment for many scientific as well as applied analytic purposes some form of generic human environment interaction model appears desirable, because it would allow for a better separation of the environmental or architectural analysis from the specific empirical questions. Therefore, individual findings would be generally better comparable and transferable on novel situations.

The main requirements of such a generic description model can be defined as capturing the behaviorally relevant aspects of an environment in a condensed form and being at the same time biologically plausible and backed by psychophysical evidence. For example, a place graph whose nodes contain both local pictorial and spatial information similar to an isovist, or a visibility graph additionally including surface properties appear already as powerful and flexible operationalizations of physical structures in general. Additionally, a framework to attach generic semantic content to the individual graph nodes would also offer a representational basis for high level analyses.

Despite this wide overlap in requirements and interests, some basic differences will probably remain mainly in the operationalization of this generic environmental representation: While architectural analyses may normally consider environments as a global whole, applications in cognitive science interested in individual behavior rather would have to take restricting situational and temporal factors into account such as prior knowledge, a sensory horizon, capacity limits of the human working memory, or task-specific strategies and heuristics, that together lead to a much higher complexity level. Yet as soon as one can abstract from individual behavior and general inter-individual tendencies and trends can be evaluated and summarized, both approaches should ideally converge to the same results. All in all, the general direction of a behaviorally and cognitively oriented architectural and environmental analysis appears as a promising approach to bring both disciplines closer together and, most important, thereby further in their specific questions.

References

Arbib, M. & Lieblich, I. (1977). Motivational learning of spatial behavior. In J. Metzler (Ed.), *Systems Neuroscience* (pp. 221–239). New York: Academic Press.

Benedikt, M. L. (1979). To Take Hold of Space: Isovists and Isovists Fields. *Environment and Planning B*, **6**, 47–65.

Byrne, R. (1979). Memory for urban geography. *Quaterly Journal of Experimental Psychology*, **31**.

Chown, E., Kaplan, S., & Kortenkamp, D. (1995). Prototypes, location and associative networks (plan): Towards a unified theory of cognitive mapping. *Journal of Cognitive Science*, **19**, 11–51.

Franz, G., von der Heyde, M., & Bülthoff, H. H. (2005). Predicting experiential qualities of architecture by its spatial properties. In B. Martens & A. G. Keul (Eds.), *Designing Social Innovation: Planning, Building, Evaluating*, pp. 157–166 Cambridge, MA. Hogrefe and Huber. in press.

Franz, G. & Wiener, J. M. (2005). Exploring isovist-based correlates of spatial behavior and experience. In A. van Nes (Ed.), *Proceedings of the 5th International Space Syntax Symposium* Delft, NL. TU Delft Press. accepted.

Franz, M. O., Schölkopf, B., Mallot, H. A., & Bülthoff, H. H. (1998). Learning view graphs for robot navigation. *Autonomous Robots*, **5**(1), 111–125.

Gillner, S. & Mallot, H. A. (1998). Navigation and acquisition of spatial knowledge in a virtual maze. *Journal of Cognitive Neuroscience*, **10**, 445–463.

Hillier, B. (1996). *Space is the Machine*. Cambridge, MA: Cambridge University Press.

Hillier, B. & Hanson, J. (1984). *The Social Logic of Space*. Cambridge, UK: Cambridge University Press.

Hölscher, C., Meilinger, T., Vrachliotis, G., Brösamle, M., & Knauff, M. (2005). Finding the Way Inside: Linking Architectural Design Analysis and Cognitive Processes. In C. Freksa, M. Knauff, B. Krieg-Brückner, B. Nebel, & T. Barkowsky (Eds.), *Spatial Cognition IV - Reasoning, Action, Interaction. International Conference Spatial Cognition 2004*, Vol. 3343 of *Lecture Notes in Computer Science* (pp. 1–23). Berlin, Germany: Springer.

Hübner, W. & Mallot, H. A. (2002). Integration of metric place relations in a landmark graph. In J. R. Dorronsoro (Ed.), *International Conference on Artificial Neural Networks (ICANN 2002)*, No. 2415 in Lecture Notes in Computer Science, pp. 825–830. Springer Verlag.

Kuipers, B. (1978). Modeling spatial knowledge. *Cognitive Science*, **2**, 129–153.

Kuipers, B. (2000). The Spatial Semantic Hierarchy. *Artificial Intelligence*, **19**(1-2), 191–233.

Kuipers, B., Tecuci, D., & Stankiewicz, B. (2003). The skeleton in the cognitive map: a computational and empirical exploration. *Environment and Behavior*, **35**(1), 80–106.

Küller, R. (2001). The architectural psychology box of infinite knowledge. In *Aesthetics, well-being and health: essays within architecture and environmental aesthetics* (pp. 129–142). Aldershot, UK: Ashgate.

Leiser, D. & Zilbershatz, A. (1989). The Traveller: A Computational Model Of Spatial Network Learning. *Environment and Behavior*, **21**(4), 435–463.

Lynch, K. (1960). *The image of the city*. Boston, MA: MIT Press.

Mallot, H. A., Franz, M. O., Schölkopf, B., & Bülthoff, H. H. (1997). The view-graph approach to visual navigation and spatial memory. In W. G. et al. (Ed.), *Proceedings of the 7th International Conference on Artificial Neural Networks, ICANN 97, Lausanne, Switzerland* Berlin. Springer Lecture Notes in Computer Science.

Mallot, H. A. & Gillner, S. (2000). Route navigation without place recognition: what is recognized in recognition-triggered response?. *Perception*, **29**, 43–55.

Mehrabian, A. & Russell, J. A. (1974). *An Approach to Environmental Psychology*, chap. The emotional correlates of single stimulus dimensions, (pp. 56–64). Cambridge, MA: MIT Press.

Moravec, H. & Elfes, A. (1985). High resolution maps from wide angle sonar. In *Proceeding of the IEEE International Conference on Robotics and Automation*, pp. 116–121 St. Louis, MO.

Peponis, J., Wineman, J., Rashid, M., Kim, S. H., & Bafna, S. (1997). On the description of shape and spatial configuration inside buildings: three convex partitions and their local properties. *Environment and Planning B*, **24**, 761–781.

Schölkopf, B. & Mallot, H. A. (1995). View-based cognitive mapping and path planning. *Adaptive Behavior*, **3**(3), 311–348.

Steck, S. D. & Mallot, H. A. (2000). The role of global and local landmarks in virtual environment navigation. *Presence. Teleoperators and Virtual Environments*, **9**(1), 69–83.

Turner, A. (2001). Angular Analysis. In J. Peponis, J. Wineman, & S. Bafna (Eds.), *Proceedings 3rd International Space Syntax Symposium*, pp. 30.1–30.11. A. Alfred Taubman College of Architecture and Urban Planning, University of Michigan.

Turner, A., Doxa, M., O'Sullivan, D., & Penn, A. (2001). From isovists to visibility graphs: A methodology for the analysis of architectural space. *Environment and Planning B*, **28(1)**, 103–121.

Turner, A. & Penn, A. (1999). Making isovists syntactic: isovist integration analysis. Paper presented at the 2nd International Symposium on Space Syntax, Brasilia.

Werner, S. & Long, P. (2003). Cognition meets Le Corbusier - Cognitive principles of architectural design. *Lecture Notes in Artificial Intelligence*, **2685**, 112 – 126.

Wiener, J. M., Schnee, A., & Mallot, H. A. (2004). Use and Interaction of Navigation Strategies in Regionalized Environments. *Journal of Environmental Psychology*, **24**(4), 475 – 493.

Wiener, J. M. & Franz, G. (2005). Isovists as a means to predict spatial experience and behavior. In C. Freksa, M. Knauff, B. Krieg-Brückner, B. Nebel, & T. Barkowsky (Eds.), *Spatial Cognition IV - Reasoning, Action, Interaction. International Conference Spatial Cognition 2004*, Vol. 3343 of *Lecture Notes in Computer Science* (pp. 42–57). Berlin, Germany: Springer.