INFORMATION NAVIGATION IN GENERATIVE DESIGN SYSTEMS

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Abstract. Generative design systems take an active part in the generation of computational design models. They make it easier for designers to explore conceptual alternatives, but the amount of information generated during a design session can become very large. Intelligent navigation aids are needed to enable designers to access the information with ease and low cognitive loads. We present an approach to support navigation in generative design systems. Our approach takes account of studies related to navigation in physical environments as well as information navigation in electronic media. Results of studies from the physical environment and electronic media reveal that 1) people exhibit similar cognitive behaviors (spatial cognition and the use of spatial knowledge) while navigating in physical and information spaces; and 2) the information space lacks legibility and imageability. The proposed information navigation model takes these findings into account.

1. Introduction

Imagine a designer who is solving a design problem with the assistance of a generative design system. The system accepts an explicit representation of the requirements to be satisfied, called a *problem*, which the designer can modify interactively and dynamically. The system is able to use these requirements when it assists the designer actively in the generation of solutions satisfying the requirements. The designer first defines the problem (A) in the system. Realizing that the problem is too complicated, she decomposes the problem into five sub-problems (A1-A5). She then starts to employ the generative mechanisms of the system to produce solutions to the sub-problems and, by combining them in different ways, two alternative solutions (S1 and S2) of the overall problem. At this point, she decides to loosen the constraints on a sub-problem (A5õ) because she is not satisfied with either S1 or S2; this, in turn, leads to an alternative formulation (A') of the top problem (A). Working on the alternative problem, she arrives at another solution (S3). She examines the solutions and decides that she should approach the design problem in yet another way. Thus, she defines a new problem (B), and continues in this manner through an arbitrary number of iterations (see Figure 1).

CAADRIA '97: Proceedings of The Second Conference on Computer Aided Architectural Design Research In Asia. Eds. Y-T Liu, J-Y Tsou and J-H Hou. April 17-19, 1997, National Chiao Tung University, Hsinchi, Taiwan. Hu's Publisher Inc., Taipei, Taiwan. pp 355-365.

We call the set of all problems and solutions a *design space*. It contains all the information a designer produces when solving a design problem. An advantage of using a generative design system to assist designers in exploring a design space is that it can speed up various steps in this process by taking an active part in both the generation and evaluation of problem formulations and solutions. At the same time, the system needs to provide proper navigation support because it makes it easy for designers to populate the design space rapidly with problems and solutions.

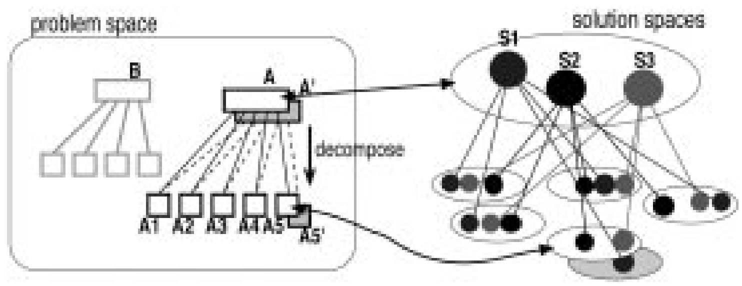

Figure 1. Design space (generated in the scenario described above)

To provide this support, two questions need to be addressed: 1) how to represent the design space? and 2) how to support designers navigating in a design space with ease and little cognitive burden? We approach these questions from two aspects. First, we examine computer systems that access or manage large amounts of information to learn how they present this information and what kind of navigation support systems they provide. Examples are database management, and hypermedia systems, World-Wide Web (WWW) browsers and geographical information systems (GIS). These computing environments manage *information spaces*, where data are organized in certain structures that are meaningful or useful to users. Second, we review the literature related to wayfinding in physical environments (or *physical spaces*) to understand the cognitive aspects of the task and the navigational supports used in physical spaces. We will then propose an approach toward design space navigation for a generative design system, which we will implement for the SEED system currently under development at CMU (Flemming and Chien, 1995).

2. Navigation in Information Spaces

2.1. NAVIGATIONAL SUPPORTS

Navigational supports in an information space have been studied early on in connection with hypertext systems and more recently with the WWW environment. In general, we can identify four basic types of *navigation operations*: go to, history, view, and search. These operations enable navigators of information spaces, respectively, to go from place to place, to retrace their steps, to see their current location in relation to its surroundings, and to look for places that are potentially interesting.

Most software systems provide these operations through consistent interaction mechanisms, which we refer to as *navigation frameworks*. Four types of navigation frameworks occur in the systems reviewed: hyperlinks, hierarchies or networks, portals or wormholes, and architectural spaces. *Hyperlinks*, such as HTTP, provide navigation through sensitive objects in an information space. *Hierarchies or networks* support navigation through linked nodes in an information space organized into hierarchies or networks (e.g., Mukherjea and Foley, 1995). *Portals or wormholes* provide navigation through interactive zooming and panning; the zoom operation can activate a portal which displays the selected information at different scales or in different formats (Bederson and Hollan, 1994), or a view through a wormhole that displays additional data related to the selected information (Woodruff et al., 1994). *Architectural spaces* use an architectural metaphor by supporting navigation through virtual spaces, such as cities, buildings, or rooms (e.g., Clarkson, 1991).

2.2. VISUALIZATION TECHNIQUES

Visualization is the key element in a navigation framework because it transforms abstract information into concrete objects that can be òseen.ó Visualization techniques can be categorized into five types: traditional methods, nodes and links, multiscale views, perspective views, and memory palace. *Traditional methods* are often used to visualize statistical information and include tables, panels, graphs, and scatter plots. *Nodes and links* are used to visualize information with hierarchical or network structures, where nodes represent data sets and links depict relationships between data sets. *Multiscale views* present information at different scales to show the data in focus (at the largest scale) as well as contextual information (Brown et al., 1993; Bederson and Hollan, 1994). *Perspective views* have been used to present multi-attribute information 3-dimensionally (e.g., Mukherjea and Foley, 1995). The *memory palace* is an ancient architectural mnemonic that associates things to be remembered with architectural spaces (Yates, 1966).

3. Wayfinding in Physical Spaces

When studying the issue of "navigation in information spaces," one cannot overlook the analogous situation of navigation in physical environments. What enables people to find their way through cities, jungles, or vast oceans? And what supports do people receive to improve their wayfinding and keep them from being lost in these environments? Studies of human spatial cognition propose *cognitive mapping* theories to answer the first question. Accordingly, researchers in the area of environment/behavior relations and environmental design address the second question and develop design guidelines for man-made spaces.

3.1. SPATIAL COGNITION

Cognitive mapping is the primary theory of human spatial cognition proposed in the literature. Discussions focus on cognitive mapping as the spatial cognition process and cognitive maps as the organizational structure of spatial knowledge. These studies are based on theories of human spatial abilities (e.g., Mandler, 1988).

Our daily spatial tasks are based on spatial knowledge gathered from the environment (Brown, 1932). Thorndyke and Goldin (1983) describe spatial knowledge in terms of three levels of information: landmark, procedural, and survey knowledge, where each level builds on previous levels. *Landmark* knowledge covers the perceptually salient objects (Golbeck, 1985) in the environment. *Procedural* knowledge (or route knowledge) encompasses information about the sequence of actions required to follow a particular route. *Survey* knowledge deals with topological information. Among the three levels of spatial knowledge, landmark knowledge is essential in human cognitive maps (Golbeck, 1985; Mandler, 1988).

3.2. ENVIRONMENTAL DESIGN

Cities and buildings are man-made spaces where most people perform daunting wayfinding tasks daily. Unfortunately, not all spaces provide adequate supports for navigation (i.e., people get lost in cities or buildings). Lynch (1960) identifies two criteria for support: legibility and imageability. *Legibility* refers to the ease with which a city's parts can be reorganized and organized into a coherent pattern. *Imageability* refers to the ease with which a place can be mentally represented. Environments with high legibility and imageability are easier for people to navigate in than those with low legibility and imageability. Environmental design studies aim at improving these two qualities of man-made environments based on the understanding of human spatial abilities.

Lynch identifies five functional elements of a city: paths, edges, districts, nodes, and landmarks. *Paths* are channels of movement, such as walkways, streets, railroads, and so on. *Edges* are boundaries between regions, such as walls or rivers. *Districts* are sections of a city that are distinct by having some common, identifying characteristics. *Nodes* are spots in a city where the observer can enter, for example, mass transit stations or bus stops; they are usually the connections of paths. *Landmarks* are point-references that are external to the observer. To ensure legibility of each functional element, Lynch advocates singularity or figure-background clarity and form simplicity for the design of districts; continuity and clarity of joint for designing edges and paths; and dominance for landmark design.

Passini (1984) describes the elements of environmental design in three categories: signs, organization, and maps. *Signs* are simply used to communicate information such as directions to a place, identity of a place, or reassurance. *Organizational elements*, which contain Lynch's five functional elements of a city, can improve legibility and imageability of a space. *Maps* provide survey information. Passini takes a process-oriented approach to environmental design and suggests a seven-step design method to guide designers. His goal is to design environments that facilitate wayfinding tasks by providing necessary environmental information without sensory or information overload.

4. Information Space vs. Physical Space

Although information navigation has been a research focus for the past few years, few formal studies have examined to what extent navigational behavior in computing environments is affected by human spatial cognition. Very few systems (e.g., Ingram and Benford, 1995) take account of cognitive mapping theories and environmental design principles, and none of them provides evidence to support the researchers' claims. A recent study on wayfinding in virtual environments demonstrates that "real-world wayfinding and environmental design principles are effective in designing virtual worlds which support skilled wayfinding behavior" (Darken, 1996). Further studies are necessary to validate such claims because of obvious differences between physical and information spaces.

Differences between the physical space and information space can be grouped into three areas: contents, structure, and human-space relation. The contents of a space constitute the primary distinction between the two types of spaces. A physical space contains a wide variety of stimuli and cues, whereas in the information space, cues are mainly visual and sometimes auditory. The overall structure of physical space is stable, but that of the information space is dynamic. Finally, people navigate "inside" the physical space; i.e., they are submerged in the space. But navigation in the information space is a remote operation; i.e., users are "outside" the information space.

But there are also similarities between navigation in the physical space and information space: use of sequential wayfinding strategies, visual references, and levels of abstraction. A sequential wayfinding strategy memorizes and recalls a sequence of movements; it is a rudimentary human spatial ability (Brown, 1932). Similarly, when navigating in the WWW, people remember sequences of locations to reach a certain web-site or utilize history tools provided by WWW browsers. Prominent visual references in physical spaces are landmarks. Although landmarks are difficult to identify in information spaces, people usually extract visual references (such as special icons) from the information and use these references later to verify if they are on a correct path. Finally, people have different cognitive maps (or cognitive collages, or images), each of which represents the same physical space (city) at a different level of detail or is based on a different viewpoint (Lynch, 1960; Tversky, 1993). Providing information at different levels of abstraction has long been supported in information spaces, particularly by GIS and database visualization systems.

The similarities between navigation tasks in physical and information spaces suggest that cognitive mapping and environmental design principles may be of use in information space navigation. But the differences have to be taken into account. Differences of contents can be alleviated by visualization techniques; i.e., by additional cues or other methods to allow landmark identifications. The structural differences, however, are not as easy to handle. One approach is to show in some way, that there is a coherent structure underlying the space. The knowledge of this structure will help the user to anticipate the kind of changes that will take place or to predict certain behaviors of the system without being surprised by system responses. Differences of human-space relations are not our immediate concern because there is little evidence to show which form of navigation (inside or outside) is easier or better.

5. Model of Design Space

Literature survey reveals that information spaces lack legibility and imageability. One of Lynch's principles of city design is to improve these qualities by providing a clear structure or hierarchy of the spaces in a city. However, the structure of design spaces is dynamic. Thus, navigation aids for generative design systems cannot start with a given static structure. But we can provide the user with a model of how a design space grows and evolves along predictable òdimensions.ó

5.1. STRUCTURE OF DESIGN SPACE

A *problem* is a set of design requirements and other specifications that describe desired properties of an artifact to be designed. As we have seen in Figure 1, a problem evolves dynamically during the course of a design project as a designer iterates through problem formulation/solution cycles. The set of all possible problem formulations that a designer can define in the context of a given design project constitutes the *problem space* of this project. The designer can decompose a problem into sub-problems or revise a problem as needed. The decomposition of a problem forms a *problem hierarchy*, and revisions of a problem constitute a *revision history*. Therefore, the position of a problem in a problem space can be uniquely identified through its positions in the associated problem hierarchy and revision history. We denote a problem by $P_{p,q,r}$, where p is the super-problem of which P is a direct sub-problem, and q and r are indices giving the position of P in a problem hierarchy and revision history respectively: i.e., P is the r^{th} revision of the q^{th} sub-problem of p. A problem space is thus the set

{ $P_{p,q,r}$ },
where: p iterates through all super-problems,
q iterates through all sub-problems of p, and
r iterates through all revisions of the q^{th} sub-problem of p.

If a problem is the root of a problem hierarchy, the index p is NULL. This is a special case. Index q identifies a position among sibling problems that are at the same problem decomposition level. It is never NULL because a problem is always located at a valid decomposition level, be it the root level, the leaf level or any level in-between. In addition, a problem is a revision of itself; therefore, the index r will never be NULL.

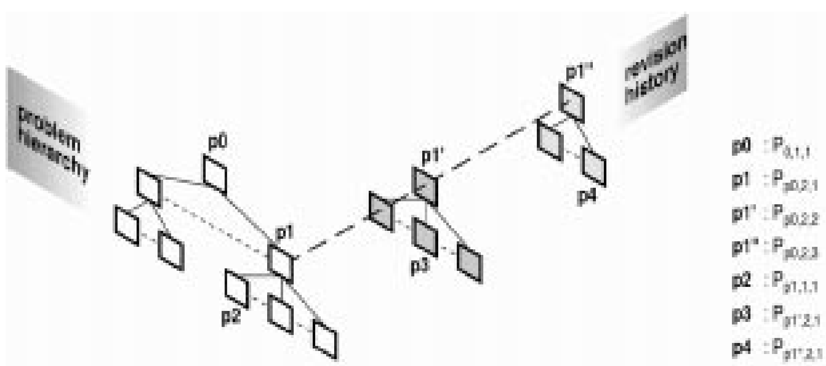

Figure 2. An example of problem space (indices are ordered from left to right)

A *solution space* is a collection of all solutions (partial or complete) to a given problem generated by the designer. In generative design systems, solutions are typically generated or derived from other solutions through mechanisms provided by the system. This derivational relationship is hierarchical and called a *solution hierarchy*; for instance, it can establish the order of rule applications in shape grammar systems. The position of a solution S in a design space can be identified through its associated problem and position in a solution hierarchy: $S_{(Pp,q,r),s,t}$, where

$P_{p,q,r}$ is a problem, s is the deriving solution and t gives the position of S in a solution hierarchy. Thus, a solution space for a problem is the set

$\{ S_{(Pp,q,r),s,t} \}$,
where: $P_{p,q,r}$ identifies a version of particular problem at a particular level,
s iterates through all deriving solutions, and
t iterates through all derived solutions of s.

A *design state* in the design space represents a partial or complete design solution of a design problem. A *design space*, is the set of all problems, sub-problems (given by their positions relative to the problem hierarchy), problem revisions (given by their positions in a revision history of a sub-problem), and solutions (given by a deriving solution and a position relative to the solution hierarchy).

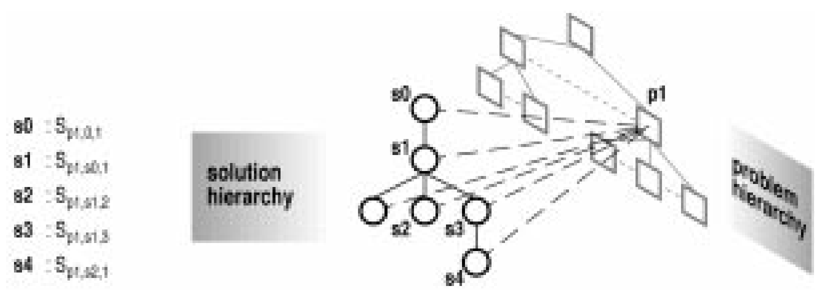

Figure 3. An example of solution space (indices are ordered from left to right)

Taken together, the five indices p, q, r, s, and t establish a structure that is independent of a specific design space. The structure remains stable independently of the way in which the space grows: objects can be added along any dimension an arbitrary number of times, but these additions always happen along exactly one of the *dimensions* p, q, r, s, and t. These dimensions are *extrinsic* attributes of a problem or solution. They can be used, in principle, to identify or visualize its position in the design space. *Intrinsic* attributes are inherent to an object and must be displayed by other means. But it is important to note that these dimensions are not analogous to the dimensions or axes of a Cartesian coordinate space. In design spaces, dimensions can vary only relative to the current value of the preceding dimensions, which puts significant restrictions on the navigation operations available to users. On the other hand, these local variables provide a principled way of navigating the space, while being able to keep track of additions or deletions of objects as the design progresses. The unfolding of dimensions in cyberspace by Benedikt (1991) is the approach that is of interest here (see Figure 4).

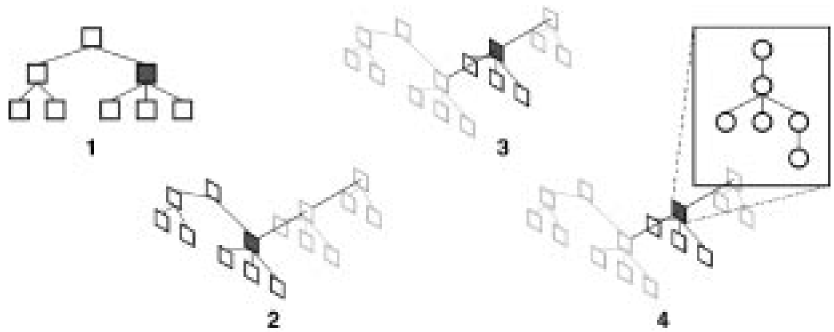

Figure 4. An example of node unfolding in a design space.
(1) depicts a node (in dark shade) within a problem hierarchy. (2) shows a revision history dimension unfolded. (3) shows a move along the revision history dimension. (4) illustrates an unfolded solution hierarchy dimension.

5.2. NAVIGATION OPERATIONS

A problem or solution forms a *node* in the associate design space whose position in the space is given by three (problems) or five (solutions, states) dimensions. We believe navigation aids should, at a minimum, show the designer at any time the location of an active node in terms of its dimensions and aid the designer in revisiting nodes that have been generated before. To achieve these two goals, we propose four basic operations:

Show location of node. A node in the design space can be identified through up to five dimensions. Showing its location means displaying the node as well as its surroundings along the relevant dimensions. The designer should be able to control the extent of the surroundings to be displayed.

Mark node. This operation allows designers to identify a specific node and tag it with a marker. The marker is a shortcut to identifying the location of a node. In addition, it adds a visual attribute to the node, which makes it visually distinct from unmarked nodes. We envision this operation to provide similar functions to those provided by landmarks in physical spaces.

Go to node. Designers can move to a node through a representation of the node displayed on the screen, or by other means provided by the user interface to the design space.

Step. This operation allows designers to move forward and backward from a node along any one dimension at a time. For example, a step backward along the p dimension brings the new location to the super-problem of the current node and a step forward along the t dimension brings the location to the next sibling solution of the current node.

6. Conclusion

We have described a model of a multi-dimensional design space for generative design systems that supports information navigation through that space in a principled manner. This model provides a clear structure of design spaces to overcome the lack of legibility and imageability in information spaces. In addition, the model supports basic navigation operations to assist designers in moving around in multi-dimensional design spaces. The model results from a survey of the literature on navigation in physical and information space (Chien and Flemming, 1996). However, the model must be validated through prototype implementations and user testing.

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