Topologic and Metric Decision Criteria for Wayfinding in the Real World and the WWW

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ABSTRACT.
There are many strategies for wayfinding strategies in the physical world and the World Wide Web (WWW). The decision processes of these strategies use various cues from the environment, such as topologic relations, information from other navigators, images of places, semantics of objects, and metric information. This paper discusses how the representation of the goal and the environment in the agent's cognitive map influence the decision criteria applied during the wayfinding process. We give a classification of decision situations that use one or several attributes as input, and look at the role of the user's preferences for decision-making. Two wayfinding simulations demonstrate the combination of goal-dependent criteria and preferences both for the physical world and the WWW.

KEYWORDS: Decision criteria, wayfinding, topology, Web space

1 Introduction

An increasing number of papers in the literature discuss the mapping of various aspects from the physical world to the Web, e.g., landmarks (Sorrows and Hirtle 1999), direction of movement (Dahlbäck 1998), and spatiality (Dieberger 1995). There is not yet a comprehensive picture of how similar wayfinding in the physical world and the WWW are. Web users think of the Web as a kind of physical space in which they move although the Web is not physical and Web users do not locomote (Maglio and Matlock 1998). An explanation is given by the theory that humans structure the real world and Web space using similar spatial image schemata, which express topologic relations between objects. Topologic relations can be extended with metric information, e.g., distances between places, so that the navigator has vector knowledge of elements in an environment. This holds at least for the physical world and for immersive Virtual Reality systems (Dahlbäck 1998).

The complexity of real world environments is depicted by various models that describe an environment or its mental representation. The models stress various features of the environment, depending on the task. Most of them use several layers—e.g., the SSH-structure (Remolina, Fernandez et al. 1999), the three-layered model of data acquisition by Siegel and White (1975), the five-tiered structure of the cognitive map presented in (Kuipers 1978)—or they organize mental maps hierarchically (Hirtle and Jonides 1985). Other models use specific metaphors to describe the representation of human knowledge, e.g., the cognitive collage (Tversky 1993).

The goal of this paper is to show how a navigator makes use of several types of information for wayfinding decisions in the physical world and the Web. The examples presented specifically refer to the use of topologic and metric information.

Sections 2 and 3 highlight the importance of topology and metric decision criteria for spatial tasks—such as wayfinding—in the real world by reviewing existing work. Section 4 explains why the WWW can be described spatially. Section 5 demonstrates the effects of goal representation and other factors, such as time and emotions, on the decision criteria applied. In section 6 we present a framework of how several decision criteria can be combined. Section 7 shows two test cases where topologic and metric decision criteria are applied. One deals with wayfinding in an airport (navigation in the real world) and the other one with purchasing something via the Internet (navigation in the WWW). In section 8 we present conclusions and suggest directions for future work.

2 Topology

2.1 Structuring Space

Topologic relations structure space. Several topologic categorizations of environments are suggested in the literature. Lynch (1960) mentions five urban design elements to describe the setting of a city. Arthur and Passini (1992) give a typology based on the structuring features of built environments, called circulations. The 4-intersection theory of topologic spatial relations between sets (Egenhofer and Franzosa 1991) defines relations in terms of the intersections of the boundaries and interiors of two sets. Evidence for cognitive hierarchical organization of space was deduced from distance and direction judgments (Hirtle and Jonides 1985).

Recent developments in cognitive science suggest that spatial relations do not exist in the real world but in our mind (Mark and Frank 1996). Due to the physiological similarities between human beings, most people experience their environment in similar ways. Johnson (1987) claims that our experience and interaction with the environment is based on the use of recursive, imaginative patterns, so-called image schemata. Many image schemata are inherently spatial, i.e., spatial image schemata express topologies. Image schemata can be used to structure an airport environment during wayfinding (Raubal, Egenhofer et al. 1997). In interviews Matlock and Maglio (1996) found that Web users often refer to the Web as a multidimensional landscape and that they use at least two image schemata. A phrase like "in Yahoo" expresses the CONTAINER schema, whereas "at Alta Vista" suggests using the PLATFORM schema.

2.2 Topology in Spatial Tasks of the Real World

Some models of wayfinding reported in the literature stress the importance of topologic knowledge for the wayfinding process, e.g., the TOUR-model (Kuipers 1978). In general, the kind of spatial knowledge needed for problem solving depends on the task that needs to be solved. For the construction of a precise map one needs *quantitative* knowledge. This allows the map user to predict precisely at which location an object will be encountered. On the other hand, to describe a location to be *identified* in the real world, a limited amount of *qualitative* knowledge may suffice. For example, neighborhood relations describing the arrangement of objects and locations are important features of spatial situations, which are relevant in spatial problem solving tasks. Topology is also relevant for wayfinding in the real world because movement in space is possible only between neighboring locations (Freksa 1991).

Golledge (1997) claims that the human search space is invariably sectoral and may be guided by even a small piece of information. A constrained set of production rules can guide segment selection by eliminating actions that appear to direct the traveler from the target direction. Let us consider a river that is aligned in east-west direction and separates a city into two districts (a northern and a southern). When reaching an intersection on the southern side, close to the river, even the small piece of knowledge that the destination is north of the river can be used to make the correct decision.

3 Metric Decision Criteria Applied in the Real World

In section 2 we discussed the role of topologic relations for wayfinding in the real world. In addition, metric information of the environment and the navigator himself, can improve the decision results. This section gives examples of metric decision criteria that can be applied if metric information about the goal is given.

If the navigator knows the structure of the environment, e.g., through reading a map, he can *plan* the route from his position to the destination. If the metric representation of objects in the navigator’s mental map is correct, the plan will result in an optimal path. Many experiments have been performed to determine how people plan routes when using maps. Golledge (1995) had subjects decide among three given routes in several, slightly changed environments on a map. He tested the subjects' preferences for the following criteria: fewest turns, longest leg first, preference for curves, preference for diagonals, shortest route, and most scenic route. He found that decision criteria are influenced by changes in the structure of the environment. For example, the preference to choose the shortest path criterion varied from 54% to 90% between slightly changed environments. The reason why people's route choices on a map are asymmetric, is discussed in (Bailenson, Shum et al. 1998) among others.

If the environment is *unknown* to the navigator (but he knows the relative position to the target), decision-making results in a route that is *locally* and not globally optimal. A method that can be applied under such conditions is vectorial navigation, which is based on path integration—allowing the navigator to determine his relative position to the origin (and therefore to the target) during the navigation process. If the navigator cannot move directly in the target direction because it is obstructed (e.g., in a street network of a city), a rule of thumb is to select the street segment that lies most in line with the target direction (Hochmair and Frank forthcoming). Deviations from a pre-planned route in an unknown environment may stem from unexpected obstacles or gaps. Strengthening cues such as landmarks are therefore helpful to the navigator. Other navigation methods that use local decision criteria with reference to a metrically known target are road climbing, a gradient or descent strategy, or systematic search strategies.

4 Spatiality of the WWW

The WWW—an electronic space—consists of Web pages and connecting hyperlinks. Its elements cannot be touched physically, because the Web space is a virtual construct of electronic hypermedia documents on different physical servers. The structure of the WWW typically follows other than *metric* concepts (Dahlbäck 1998). This fact influences the navigation means and strategies applied in the WWW. They differ from those used in the physical world in the way that spatial directions and Euclidean distances are less frequently used for decision-making. Despite this, the WWW is said to be *spatially* organized. This is reflected by the classification of Dourish and Chalmers (1994), who distinguish between three modes of navigation in information spaces: *spatial*, *social*, and *semantic*.

Spatial metaphors in a user interface are used to compensate for the lack of metric spatiality of a domain while mapping physical space relations to abstract domains. Kuhn (1996) claims that a domain that should function as an appropriate source of spatialization, must be inherently spatial from the user's perspective. This is the case for domains containing geographic information, or information that has some commonly agreed internal structure (Dahlbäck 1998). Visualization of geographic information can be accomplished through a direct visualization of metric relations, such as coordinates of hotels in a summer resort. In contrast, the visualization of information about domains that are not real physical spaces, but have some commonly agreed internal structure, relies on spatial image schemata, such as CONTAINER or NEAR-FAR. Examples of such spaces that can be generalized through topologic relations and are independent of metric description are social places such as cities (Dieberger and Frank 1998) or a computer desktop (Kuhn and Frank 1991).

The user interface with its ability to visualize the topologic and metric Web structure within a map site (e.g., visited nodes as paths) helps to strengthen the spatial character of the Web. Topologic and metric relations allow for defining the *neighborhood* of Web pages, the *distance* between Web sites, the *direction* of movement in a domain, or a Web page as a *landmark*.

5 The Role of Goal Representation for Decision Criteria

A place in the real world and the WWW can be defined by several representations. As demonstrated in the previous sections both real world space and Web space include among others metric, topologic, and semantic properties. All types of information with their combinations, can in principle be used to describe a place in an environment. For example, a building in the real world can be defined by

- a coordinate tuple in a map (metric knowledge);
- move and turn sequences (topologic knowledge, possibly combined with metric knowledge);
- the name of the building (semantic knowledge);
- its address (topologic and semantic knowledge).

A Web page might be described by

- a chain of links (topologic): hereby, *link*, *Web page*, *goal*, and the neighborhood relation are topologic elements as part of the wayfinding process;
- its URL (topologic and semantic): from the numbers of directories mentioned in the link one can derive the depth of the Web page in the domain, the name of a Web page (*name.htm*) represents a keyword of its content;
- its content (semantic and topologic);
- its position in a site map (topologic): sitemaps visualize the connection of Web pages in a domain, i.e., hierarchical structures and neighborhood;
- the screen coordinates of the link leading to the Web page (metric).

Depending on the mode of the goal definition, different wayfinding strategies are applied. For example, in the real world a metric criterion such as the shortest path can only be applied if—besides topologic information about the structure of the environment—the metric information of the goal is available. Metric information, on the other side, is not required, to make decisions in an airport environment or on a site-map in the Internet, because topologic and semantic information are sufficient to drive decisions.

Besides the representation of the goal, other circumstances of the wayfinding situation have an effect on the decision criteria and wayfinding method applied. For example, *time restrictions* (causing stress) influence wayfinding strategies of an urban navigator (Stern and Portugali 1999). *Emotions* such as anger caused by insufficient information on signs, may make a navigator abandon his mode of wayfinding and change to another mode, e.g., asking another person for directions.

6 The Combination of Several Decision Criteria

In this section we discuss how several decision criteria, if they are enforced by the decision situation, are handled. We thereby use *agent*—a concept from Artificial Intelligence—as a conceptual paradigm to represent the human navigator. This allows us to elaborate the problem on a more abstract and theoretical level, and to reduce the complexity of human navigation. Both spatial and non-spatial attributes provide input for decision-making. Several decision models that include the utility (attractiveness) and disutility (dangers) of places are reported in the literature, e.g., (Timmermans and Golledge 1990). They deal with the task of visiting only those nodes, which have a property of interest for the agent. We focus on a wayfinding process where the agent has a single goal and does not intend to reach several nodes. Assuming this, the combination of several decision criteria can be divided into the following cases:

1. multiattribute decision
2. 2-step decision with a sequential use of criteria

For both cases an applied decision criterion is either related to the goal, or it represents an agent's bias and is therefore independent of the goal definition. The first case describes a situation where one or more criteria are simultaneously applied to drive a *single* decision—also called *one-shot decision* (Russell and Norvig 1995)—that leads to a unique result (Fig. 1a). The second case uses also goal-independent preferences if step (1) does not lead to a unique result (Fig. 1b). The simulated decision situations in section 7 discuss the combination of a goal-related criterion (expressed through topologic relations), and a user's bias (expressed as preferred direction), i.e., decision making after case (2).

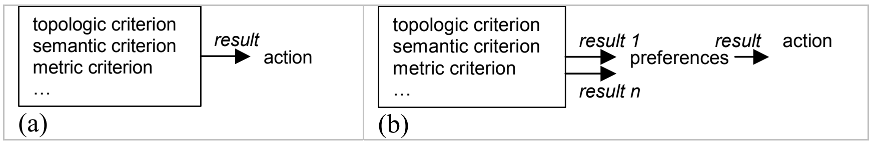

Fig. 1: Principles of multiattribute decision (a) and 2-step decision function (b)

The decision maker's evaluation of potential consequences of an alternative is described by a *utility function* that permits calculation of the expected utility for each alternative. The function maps an agent's state (after the next potential alternative chosen) onto a real number. This number describes the associated degree of happiness, and the alternative with the highest expected utility is considered the most preferable. A utility function allows for coping with situations of conflicting goals where both goals cannot be achieved to the same extent. Simultaneously the agent's familiarity with the environment plays a role for the weighting of used attributes within the utility function. Problems, in which outcomes are characterized by two or more decision criteria that are evaluated at the same time, are solved by a multiattribute utility function. Such a function might be used in an urban decision situation, where the agent has knowledge about the direction of the goal (metric knowledge) and the number of blocks to the goal (topologic knowledge).

7 Test Cases: Topologic and Metric Criteria

In this section we give two examples of wayfinding, one in an airport environment, the other in a Web domain. Both examples are simulations that describe the wayfinding process of an abstract navigating agent in these two domains. In the model we assume that the environment is unknown to the agents.

7.1 Test case 1: Navigation in the Real World

The first setting is an airport environment (Vienna International Airport), which is abstracted through a directed graph with nodes and edges (Fig. 2a). We focus on the agent's planning and decision-making. For details about the agent's architecture, the information flow, and the environment see (Raubal 2001). Nodes represent decision points where the agent perceives information from signs and edges represent possible movement of the agent between nodes. The agent's goal is defined as the gate 'C 54', which is identified by a letter and a number. The agent starts its navigation at node 1 (i.e., the check-in counter) (see Fig. 2a) and tries to find its way to the goal.

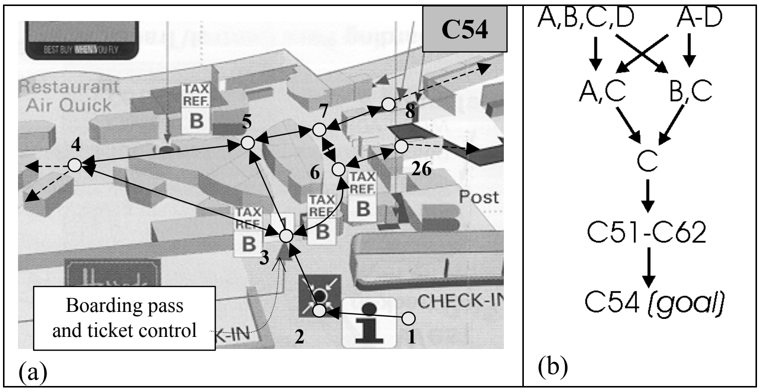

Fig. 2: A part of the Vienna International Airport abstracted as a graph (from Raubal 2001) (a) and the agent's cognitive map used to navigate in this environment (b)

Due to the agent's experience its cognitive map contains topologic relations between places of an airport: The gates are embedded within a hierarchical structure that can be described with the CONTAINER image schema. For example, the goal 'C 54' is assumed to be in the container 'C51-C62', which in turn is in a container of all 'C'-gates and so on. The closer a sign leads to the element 'C54' in the topologic structure, the higher the utility of the edge connected to the perceived sign. In the simulation, the cognitive map can be simplified by dropping those hierarchical concepts that do not refer to signs in the environment. The resulting cognitive map is visualized in Fig. 2b. Thus, if an agent perceives two signs, e.g., 'A,C' and 'C', it will choose the edge connected to sign 'C' because it is mentally closer to the concept 'C54' than the concept 'A,C'.

Situations where a unique decision cannot be made only through topologic relations occur. Then, the agent needs to apply the following 2-step decision sequence during the navigation process:

a. Select those signs among the perceived signs of which the information has a minimum mental distance to the concept of the goal (topologic criterion).
b. In the case of no unique decision, take the path (among the filtered ones) with the mostly preferred direction (metric criterion).

In the airport environment, the agent's metric bias is modeled as preferred directions within the agent’s egocentric reference frame. The reference frame is represented through eight directions—front, back, left, right, and four directions in-between. Each of the eight directions is given a corresponding preference value (the direction in front is assigned the highest one). Fig. 3 visualizes a decision situation, in which steps (a) and (b) are applied within a 2-step decision sequence in the airport. The agent's position (node 3 in Fig. 2a) is denoted by the gray circle. The local reference frame is visualized as a star of arrows—direction 0 pointing to the agent's front, direction 4 pointing towards the agent's previous position (backwards). The agent perceives the signs 'A', 'A,C' and 'B,C'.

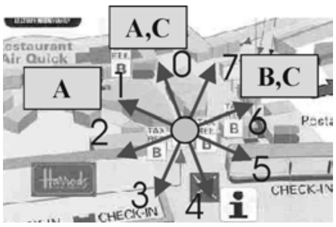

Fig. 3: Decision situation that requires semantic and metric decision-making in a sequence

Step (a) of the decision process filters the signs 'A,C' and 'B,C' because these concepts are both 3 steps from the goal 'C54' in the cognitive map (see Fig. 2b), and the concept ‘A’ is not part of the cognitive map. In step (b) the agent applies its preference to the direction of the two filtered signs. As the front direction 0 is given the highest utility, the agent chooses the path indicated by the sign 'A,C'.

7.2 Test case 2: Navigation in the WWW

The example for WWW navigation is situated in the directories at the portal of the Yahoo search engine *(http://www.yahoo.com/)*. The Web environment is abstracted as a directed graph, which is visualized in a simplified version in Fig. 4. The nodes of the graph represent the Web pages and decision points, whereas the edges represent the hyperlinks between pages. Edges are compound objects that consist of a start- and endnode, and contain semantic or topologic information. Web domains show a hierarchical structure and are constructed from several categories where the categories are organized as taxonomies or partonomies. Terms of up-links in the categories are printed in italic font and gray, those of down-links in regular font and black. Cross-links between categories are visualized as dashed arrows. Besides its topologic or semantic information, a link also has a metric position in the interface (see Fig. 5 left side). In the Web environment we model the agent's metric preference as the nearness of a link to the upper border of the user interface.

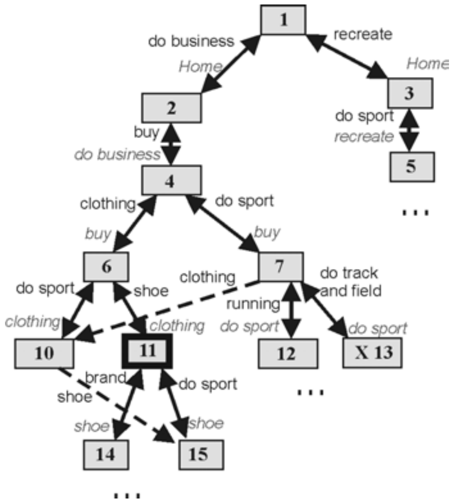

Fig. 4: Simplified abstract structure of the Yahoo-directories

The agent's goal is to find a Web page within the hierarchical structure, on which it can purchase sneakers of a certain brand and size. Each of these demanded properties is embedded within a hierarchical network (abstracted as graph)—the element of the lowest hierarchical level in each graph defining the demanded concept (see Fig. 5 right side). The complete cognitive map consists of five graphs, which include the concepts of user-intended actions, physical object hierarchy, action affordances, brand, and size (Hochmair and Frank 2001). Some of the abstract graphs are based on 'IS-A' relations. For example, the agent assumes that 'running' is a kind of sport. If we spatialize the 'IS-A' relation with a spatial metaphor (Kuhn 1996), e.g., through upper-lower relations, the hierarchy describes *topologic* relations between the concepts, similar to the airport example.

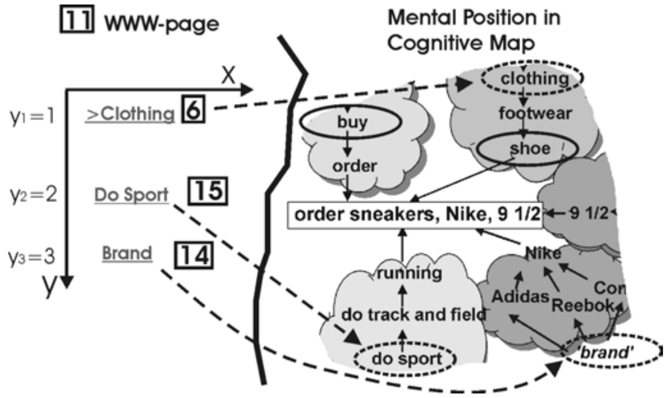

Fig. 5: Links as perceived in the interface at a decision point (left) and corresponding concepts in the agent's cognitive map (right)

As discussed in the airport case study, the example visualized in Fig. 5 enforces the use of topologic knowledge and metric bias within a 2-step decision situation. Let the agent's position be at node 11 in Fig. 4. The agent has reached this node via the path 1-2-4-6-11. The mental position then consists of the concept 'shoe' for the graph of the physical object hierarchy, and the concept 'buy' for the user-intended actions, i.e., the agent has perceived links with this information during the navigation process so far. It is visualized as circles in the cognitive map (right side of Fig. 5). The agent perceives three links ('clothing', 'do sport', 'brand'), where 'clothing' is the top-most and 'brand' is bottom-most in the user interface (left side in Fig. 5). The positions of the corresponding concepts in the cognitive map are visualized as dashed circles.

At the beginning of the decision process, the percept 'clothing' is skipped from the potential decision alternatives, because the mental position 'shoe' in the corresponding graph is closer to the target ('shoe' is even the target for this graph). Step (a) of the 2-step decision results in the two remaining concepts 'do sport' and 'brand' as the topologic distance to the corresponding goal amounts to 2 steps for each of the concepts (Fig. 5). As no unique result can be found with topologic decision-making, step (b), i.e., the metric bias, is applied. The link 'do sport' is more to the top in the interface than the link 'brand', therefore the metric bias gives a unique result, and the link 'do sport' is chosen for the next step.

8 Conclusions

We discussed the combination of various types of information for wayfinding in the real world and the WWW. We gave a categorization of decision making situations: A decision either gives a unique result through the goal related decision criteria, or it needs to additionally apply an agent's bias. Which criteria are applied, and how they are weighted, largely depends on the representation of environment and goal in the agent's cognitive map.

We showed an example for a one-shot decision situation in an airport environment and the Web, which applies goal-related topologic criteria and metric preferences. For future work one needs to investigate the specific *interplay* of topologic, metric, semantic, and other decision criteria for multiattribute decisions. This would imply taking a closer look at the navigator's mental representation. In order to assess the results of the presented test cases, one needs to compare them to the results of human subjects testing. Such a comparison will also help to test the plausibility of the proposed criteria and strategies for the agent, and find additional ones to be included.

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