A Formal Model of the Process of Wayfinding in Built Environments

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Abstract. Previous recent research on human wayfinding has focused primarily on mental representations rather than processes of wayfinding. This paper presents a formal model of some aspects of the process of wayfinding, where appropriate elements of human perception and cognition are formally realized using image schemata and affordances. The goal-driven reasoning chain that leads to action begins with incomplete and imprecise knowledge derived from imperfect observations of space. Actions result in further observations, derived knowledge and, recursively, further actions, until the goal is achieved or the wayfinder gives up. This paper gives a formalization of this process, using a modal extension to classical propositional logic to represent incomplete knowledge. Both knowledge and action are represented through a wayfinding graph. A special case of wayfinding in a building, that is finding one's way through an airport, is used to demonstrate the formal model.

Keywords. Wayfinding, Image Schemata, Affordances, Spatial Reasoning, Knowledge Frames, Logic, Graphs.

1 Introduction

In order to represent and simulate people's processes of wayfinding it is necessary to understand how people immediately make sense of spatial situations while performing a wayfinding task. The formal model of wayfinding presented in this paper is founded on a framework consisting of image schemata and affordances, both of which are useful ways to represent people's perceptual and cognitive structures. Image schemata are recurring mental patterns that help people to structure and operate within geographic spaces. An affordance is what an object, an assemblage of objects, or an environment enables people to do.

Previous research on human wayfinding has focused mainly on the exploration of cognitive representations, or what Norman [26] calls "knowledge in the head." At the same time, little attention has been paid to "knowledge in the world", such as the

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processes of wayfinding and information needs [11]. Norman argues that people do not need to have complete knowledge of the space in order to behave effectively. The starting point of our model is that knowledge is distributed, partly intrinsic to the wayfinder, but also partly residing in the world and in the constraints of the world.

The model of the wayfinding process in built environments presented in this paper is similar to Kuipers' [18] TOUR model where views lead to actions, which lead to further views. Learning and problem solving while traveling in a large-scale urban environment is simulated with this model. But Kuipers focuses on knowledge representation (i.e., "knowledge in the head"), whereas our approach also takes "knowledge in the world" into account (i.e., what information can we get directly from the objects and places we observe, namely their affordances). This paper represents the process of wayfinding using a transition graph, the *wayfinding graph*, where the transitions are between views and states of knowledge. A successful navigation through the space corresponds to a traversal of the graph ending at a goal node.

Section 2 presents the case study of finding one's way from the check-in counter to the gate in an airport. Our formal model is later applied to this case study. In section 3 we review research on spatial reasoning and wayfinding, introduce the concepts of image schemata and affordances, and explain how these two concepts are related. At the end of the section a reasoning framework about observations of the empirical world based on observation schemata, observation instances, knowledge frames, and knowledge instances is described. Section 4 shows the formal model of the wayfinding process whose principal elements are a wayfinder, objects, knowledge, and actions. In section 5 the formal model is applied to a subtask of the case study described in section 2, using the wayfinding graph. Section 6 presents conclusions and suggests directions for future work.

2 Wayfinding in a Built Environment: Case Study

In order to clarify the concepts and methods used in this paper, we describe an example that illustrates the kind of situation in which our approach applies. The example concerns the problem of wayfinding in a built environment, specifically finding one's way from the check-in counter to a specific gate in an airport. In this example we use the built environment of Vienna International Airport, taken from Raubal [31] and Raubal and Egenhofer [32] (Figure 1).

The task of going from the departure hall to the gate consists of 3 subtasks that have to be performed in sequential order. People have to check in, move through passport control, and move through security control at the gate. Table 1 shows a short description of the different viewpoints people have to face while performing this task.

During interviews ([31], [32]) subjects described their spatial experiences in this airport environment while orienting themselves and navigating through the space. A sequence of color slides was used to simulate the route-following task from the departure hall to gate C57. The focus of this testing of human subjects was to receive data for the existence of image schemata in wayfinding (see also [33]). A linguistic method was applied to extract image schemata from the transcripts of the interviews. We use the resulting semi-formal image-schematic representations in section 5 to deduce affordances from image schemata.

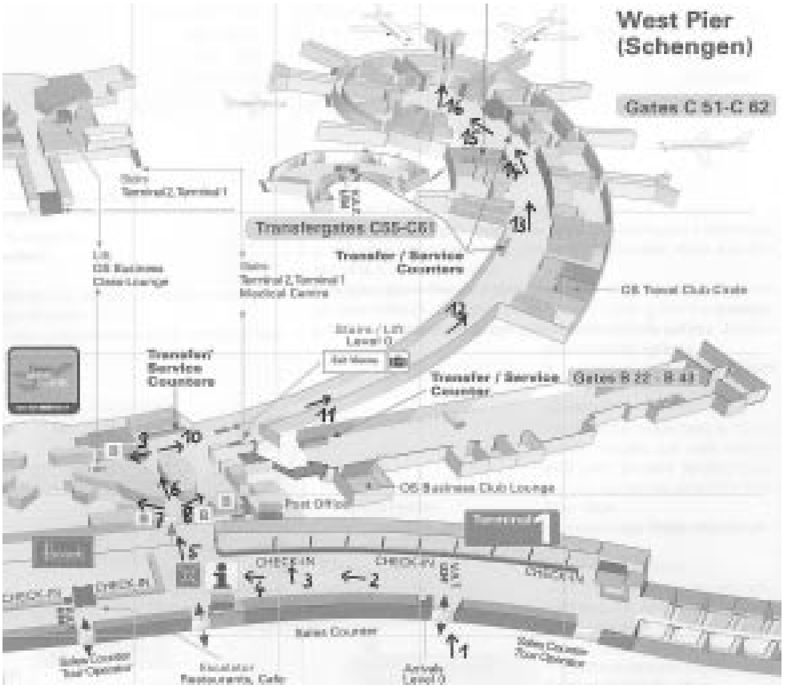

Fig. 1. Part of Vienna International Airport

Table 1. Viewpoints and their descriptions

Viewpoints	Description
1	Entrance to airport (i.e., departure hall)
2	Departure hall
3	Check-in area
4	Departure hall after check-in
5	Passport control
6, 7, 8	Duty-free area after passport control
9, 10	Duty-free area
11, 12, 13, 14	Hallway to gate area
15	Gate area
16	Gate

3 Background

3.1 Spatial Reasoning and Wayfinding

Finding one's way through a building relies on a variety of elements. People have to make intuitive and quick decisions while at the same time they must avoid getting lost. Therefore, they apply common-sense (geographic) knowledge [18] and qualitative methods of spatial reasoning ([6], [2], [5], [7]). When people perceive space through different channels they arrive at various kinds of information that are usually qualitative in nature. People also most often use topological instead of metrical information [30].

Human wayfinding is based on "a consistent use and organization of definite sensory cues from the external environment" [22]. It takes place in many different situations in which people find themselves, such as driving across a country, walking in a city, or moving through a building [11]. The ultimate goal of human wayfinding is to find the way from one place to another. People need to have spatial knowledge and various cognitive abilities to succeed in wayfinding (e.g., following a path). Spatial knowledge is assumed to consist of *landmark*, *route*, and *survey* (*configurational*) *knowledge* [35]. The cognitive abilities depend on the task at hand, e.g., finding one's way in a street network or navigating through a building. It is also assumed that people represent their environment in a *cognitive map*, i.e., a mental representation that corresponds to people's perceptions of the real world [19].

Human wayfinding research can be divided into two categories [11]: performance and competence. The literature on *performance* contains empirical results of how people find their way. Lynch's [22] principles for city design are regarded as the foundation for human wayfinding research. Weisman [36] identified four classes of environmental variables that influence wayfinding performance within built environments: (1) visual access, (2) architectural differentiation, (3) signs and room numbers to provide identification or directional information, and (4) plan configuration. Other researchers ([9], [8], [27], [28]) confirmed his results. Seidel's [34] study at the Dallas/Fort Worth Airport confirmed that the spatial structure of the physical environment has a strong influence on people's wayfinding behavior. People's familiarity with the environment also has a big impact on wayfinding performance ([9], [34]).

In addition to empirical studies of performance, cognitive wayfinding models have been investigated in what is referred to as *competence* literature. Cognitively based computer models generally simulate a wayfinder that can solve route-planning tasks with the help of a cognitive-map-like representation. Kuipers' [18] TOUR model is considered the starting point for a computational theory of wayfinding. It simulates learning and problem solving while traveling in a large-scale urban environment. Knowledge is represented through environmental descriptions, current positions, and inference rules that manipulate them. Other cognitively based computer models are ARIADNE [3], a program that learns facilitators and obstructers for pragmatic two-dimensional navigation, TRAVELLER [21], SPAM [25], and ELMER [24]. Neurologically based information processing is used in NAVIGATOR [13]. By not focusing on the processes of how people assign meaning to their spatial environments as they navigate through them, most of these models fail to incorporate components of commonsense knowledge. Therefore, Golledge [12] mentions the possibility of spatial knowledge not being well described by existing theories or models of learning and understanding.

3.2 Image Schemata and Affordances

Image Schemata. Johnson [15] proposes that people use recurring imaginative patterns, so-called *image schemata*, to comprehend and structure their experiences while moving through and interacting with their environment. Image schemata are intended to be pervasive, well defined, and of sufficient structure to constrain people's understanding and reasoning. The PATH schema, for example, represents movement and is therefore important for wayfinding. It is structured through a starting point, an endpoint, and a connection between these points.

In order to perform a wayfinding task people need to understand spatial situations and based on this understanding decide which way to go. Image schemata offer a way to describe people's immediate grasp of meaning: in order to understand the world at a particular point in time they apply image-schematic structures to spatial situations. Such a structuring process helps them to use their environment without concentrated effort (i.e., through common sense). For example, to follow a route from one place to another, people apply the PATH and SURFACE schemata. In this sense, image schemata help people to relate previous experiences with current environmental perceptions to understand the characteristics of a particular spatial situation. Relating image schemata to real-world situations is based on topological concepts; e.g., people can relate a building to the CONTAINER schema because they perceive its inside-outside structure. Image-schematic reasoning is also qualitative because people do not use absolute values, such as the exact position of an entrance within a coordinate system, in their everyday lives.

Affordances. The term *affordance* was introduced by Gibson [10] who investigated how people perceive their environment. Gibson described the process of perception as the extraction of invariants from the stimulus flux and called these invariants affordances. Affordances are what objects or things offer people to do with them. Therefore, they create potential activities for users. Norman [26] investigated affordances of everyday things, such as doors, telephones, and radios, and argued that they provide strong clues to the operation of such things. He characterized affordances as results from the mental interpretation of things, based on people's past knowledge and experiences which are applied to the perception of these things. Affordances, therefore, play a key role in an experiential view of space ([20], [23]), because they offer a user-centered perspective.

Kuhn [17] applied the theory of affordances to spatialized user interfaces. Affordances of physical space are mapped to abstract computational domains through spatial metaphors in order to bring human-computer interaction closer to people's experiences with real-world objects. Kuhn groups spatial affordances into four categories—affordances for (1) an individual user (e.g., move), (2) a user and an individual entity (e.g., objectify), (3) a user and multiple entities (e.g., differentiate), and (4) groups of users (e.g., communicate)—, reflecting different task situations. In order to know what passengers can do at an airport one has to find out what spatial affordances the architecture and objects of an airport can offer for people's wayfinding. Examples for each of Kuhn's categories in relation to airport space are "moving from check-in counter to the gate", "perceiving and interpreting a sign", "differentiating gates", and "communicating with other people at the airport."

Relation between Image Schemata and Affordances. Affordances are closely related to image schemata because both of these concepts help people to understand a spatial situation in order to know what to do. The following two examples show the connection between image schemata and affordances.

Example 1: Tom is entering the departure hall.

Example 2: Michael is going from passport control to the duty-free area.

Example 1 shows an experience with the concept of containment. *To enter* is an affordance of the object *departure hall* and, therefore, based on the CONTAINER schema. Example 2 shows the PATH schema. The path from passport control to the duty-free area affords Michael *to walk*; therefore, motion is based on the PATH schema.

Certain scenes we observe match a collection of image schemata and from these image schemata we can deduce affordances. For example: I'm in a room (CONTAINER1) and through an open door I can see another room (CONTAINER2). Based on the structure of the CONTAINER schema (inside, outside) I can now deduce the affordance of crossing the border (the door) and, therefore, moving from the inside of CONTAINER1 to its outside (which is the inside of CONTAINER2). In this case, the CONTAINER schemata are instantiated through the two rooms.

3.3 Reasoning about Observations of the Empirical World

Our knowledge of the empirical world is gained by making observations of parts of the world (a geographic space is such that it is impossible in general to observe the whole space in one observation). Previous work [40] has provided a structure for the treatment of imprecise knowledge derived from observations. Figure 2 shows the framework in which observation-based knowledge of the empirical world is structured.

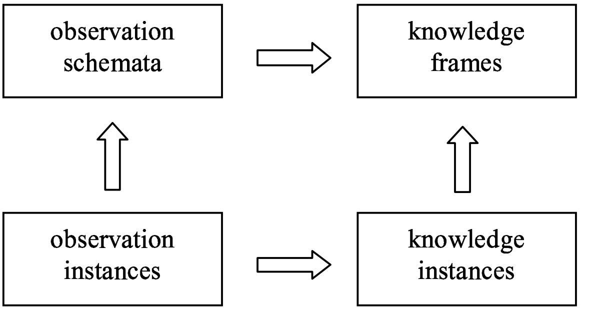

Fig. 2. Framework for knowledge of the empirical world

Observations. An *observation schema* is the framework and context in which an observation is made. The observation schema includes the spatial and temporal location at which the observation is made, the scope (spatial and semantic) of the observation, limitation of measuring instruments, and predisposition of the observer. The observation schema may lead to levels of imprecision and incompleteness in the observation instances made with respect to it.

Example: An observation of a sign to a gate area A, B, or C. Due to the positioning of the sign with respect to the observer, and the style of the sign, suppose that the observer will be unable to distinguish the letters A and C. Following the observation, an observer would either gain knowledge that the sign indicates gate area A or C, or that the sign indicates gate area B. If the observation leads to knowledge that the sign indicates gate area A or C, then imprecise (and therefore certainly incomplete) knowledge has resulted.

An *observation instance* (or just *observation*) is a specific observation made in the context of its observation schema and with respect to a particular given proposition or set of propositions. Intuitively, we make the observation so as to determine as best we can whether the propositions are true or false, but due to the imprecision of the observation we cannot in general make such a crisp determination. Thus in our example, we may make an observation of the sign to determine whether the path ahead to our goal (gate C57) is the correct one. In this case, the proposition, whose truth-value we are attempting to determine by making the observation, is as follows: The sign indicates that the gate area ahead is area C.

Knowledge. The *knowledge frame* is the framework in which knowledge can be obtained from an observation schema. This will depend on the context, precision, accuracy, and other quality measures, associated with the observation schema.

In order to formalize this, we provide a modal extension to classical propositional logic ([14], [1], [37], [4]). Suppose that the aspects of the world that we can in principle observe can be described in terms of a nonempty set of propositions. Each of these propositions is either true or false, and propositions can be combined by the usual logical operators $\wedge$ (and), $\vee$ (or), $\neg$ (not), $\rightarrow$ (implies), etc. In the example above, the propositions might be that the gate area indicated by the sign is A, the gate area indicated by the sign is B, or that the gate area indicated by the sign is C.

We can now consider the set of all possible states of the world (possible worlds in the Kripke [16] sense), where each state corresponds to a consistent valuation of all the propositions. Our example consists of the three states:

s_A, where the gate area indicated by the sign is A.
s_B, where the gate area indicated by the sign is B.
s_C, where the gate area indicated by the sign is C.

Thus, the phenomenon under observation is in one of a collection of states, each state being represented as the valuation of the propositions. If an observation were perfectly accurate and completely precise, it would identify among the possible states a single state, and that would be the actual state of the phenomena under observation. The level of precision of an observation schema can be thought of in terms of the states that are discernible by the observation schema. In the example, A and C cannot be distinguished, and this implies that regardless of the actual observation made, states s_A and s_C will not be distinguishable.

In general, a given observation schema will have associated with it a knowledge frame, and in the case of an imprecise observation schema the frame reflects the imprecision by indicating that certain states of the world are indistinguishable by any observation based on the observation schema. In many cases (and in the work done in this paper) it makes sense to consider the indiscernibility relation to be an equivalence relation that induces a partition on the possible worlds into blocks. By way of illustration, the observation schema given in our example partitions the states into blocks: $\{s_A, s_C\}$ and $\{s_B\}$.

A *knowledge instance* is the knowledge acquired from an observation. The knowledge frame associated with the observation schema will structure this knowledge. Suppose that we make a specific observation, say o, in the context of an observation schema and with respect to a particular given proposition, say p. Knowledge of proposition p is represented as $K_\mathrm{o}(p)$, itself a proposition, and taken to read that "following observation o, we know that proposition p is true." There are various combinations, some of which are listed below:

$K_\mathrm{o}(p)$	Following observation o, we know that p is true.
$K_\mathrm{o}(\neg p)$	Following observation o, we know that p is false.
$\neg K_\mathrm{o}(p)$	Following observation o, we do not know that p is true.
$\neg K_\mathrm{o}(\neg p)$	Following observation o, we do not know that p is false.

In the continuation of our example above, we made an observation of the sign to determine if the path ahead to our goal (gate C57) is correct. The knowledge gained will depend on the result of the observation. There are two cases:

1. We observe that the sign indicates either gate area A or gate area C (the observation schema does not permit distinction between these letters). Then the following modal propositions are the case:
   K_o(gate area indicated by the sign is A $\vee$ gate area indicated by the sign is C).
   $\neg K_o$(gate area indicated by the sign is A).
   $\neg K_o$($\neg$ gate area indicated by the sign is A).

2. We observe that the sign indicates gate area B. Then
   K_o(gate area indicated by the sign is B).

Suppose that we make a specific observation, say o, in the context of an imprecise observation schema and with respect to a particular given proposition, say *p*. As we have seen, we will only know for certain that *p* is true if the block of the observation schema that we observe to be the case is one for which *p* is true in all constituent worlds. If it is the case that *p* is true in some worlds of the block and false in others, then we can only say that *p* may be true. If *p* is false in all constituent worlds, then we will definitely know that the proposition is false. This is essentially the theory of rough sets ([29], [39], [38]), where for each element *x*, there are three possibilities:

x is definitely in the rough set.
x is definitely not in the rough set.
x is possibly in the rough set or not in the rough set.

4 Observation-Knowledge Structures for Wayfinding in Built Environments

In this section we describe our proposed process model for wayfinding in built environments. The main parts of the model are a wayfinder who tries to solve a route-finding task, objects within the built environment, knowledge gained from image schemata and affordances, and actions that are taken by the wayfinder based on such knowledge (Figure 3).

4.1 Objects and their Affordances

While finding their way through a built environment, people observe objects and their affordances. Objects can be things like signs, doors, paths, shops, etc. In this paper we use the term *object* in a general way. Objects do not have to be tangible and all that is required from objects here is that they can be located in a spatial scope and have affordances. Image schemata seem to fit these constraints, therefore we use them for the representation of objects, i.e., for representing spatial context. It is possible to deduce affordances from image schemata even if the object represented by an image schema cannot be exactly specified by the wayfinder. For example, the notion of an open space can be represented through the CONTAINER schema and the wayfinder can deduce affordances such as being inside, leaving it, etc. from it. Image schemata are also used to represent other types of spatial context such as height: The fact that a sign is hanging from the ceiling can be represented as IS_DOWN (sign, ceiling).

Objects offer different affordances to people finding their way. For each element *x* in a set of objects *X* there exists a set of affordances F_x. We distinguish between *information affordances* and *action affordances*. For example, a door affords both information (i.e., there is a path this way and something on the other side) and action (i.e., passing through the door to get to the other side). We represent the set of affordances as the disjoint union of two sets, i.e., I_x (information affordances of x) and A_x (action affordances of x). Formally, $F_x = I_x \dot{\cup} A_x$.

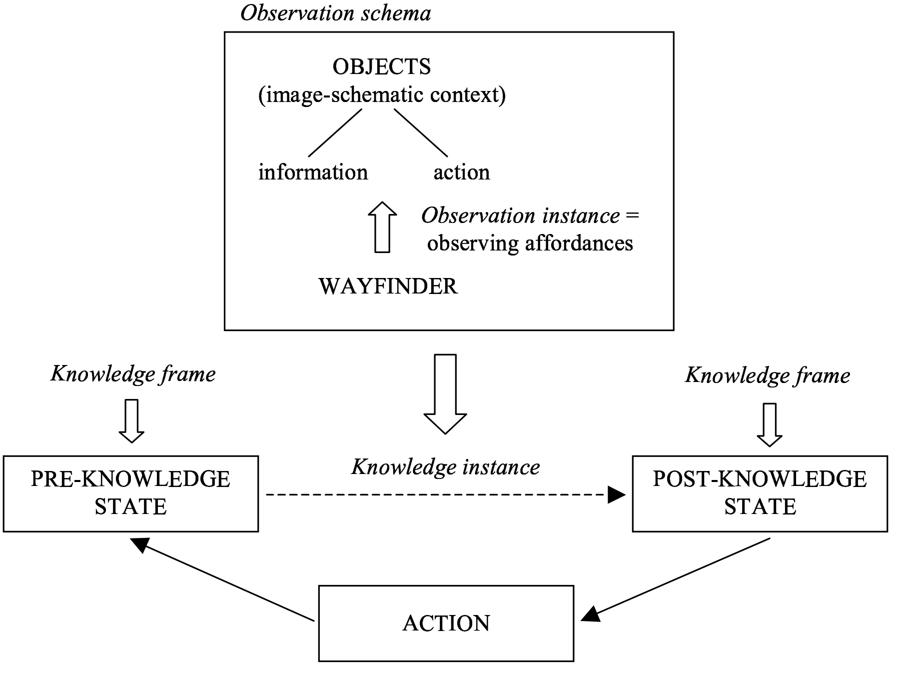

Fig. 3. Process model for wayfinding in built environments

4.2 Knowledge and Action: The Wayfinding Graph

In order to represent and simulate knowledge and action in a wayfinding situation, we use a weighted, labeled directed graph, the *wayfinding graph*. The intuition is that the nodes of the graph represent states of knowledge and current location in the wayfinding process, while the edges represent transitions either between views or between states of knowledge. Information affordances of objects in scope, lead to knowledge transitions; while action affordances of objects in scope, lead to view transitions. In real examples of the wayfinding process, information and action may be simultaneous and continuous, but our model discretizes the process and separates information and action.

More formally, an ordered pair, comprising a view state and a knowledge state labels each node of the wayfinding graph. The view state is modeled as a set of objects in scope of the current view. The incomplete knowledge state is modeled using a Kripke frame, as described in section 3. Each directed edge of the wayfinding graph is labeled by an affordance provided by one or more of the objects in the view state that is part of the ordered pair labeling the source node of the edge. If the affordance is an information affordance, then the target node of the directed edge will be labeled by the same view state but possibly different knowledge state (taking into account the knowledge gained from the information affordance). If the affordance is an action affordance, then the target node of the directed edge will be labeled by the same knowledge state, but possibly a different view state (taking into account the new set of objects in scope following the action). The affordances might be prioritized, in which case navigation of a path through the graph will be influenced by the prioritization. For ease of representation, it is sometimes useful to amalgamate a collection of viewpoints or knowledge states into a single "hypernode." We will see an example of this in the case study of section 5.

The wayfinding graph has at least two distinguished nodes, the start node where the wayfinding process begins and the goal node(s) that mark the end of the wayfinding process. We can now simulate the process of wayfinding by a traversal of the graph from the start state to one of the goal states. As the traversal of the wayfinding graph progresses, the user physically moves around the space, gaining knowledge in the process.

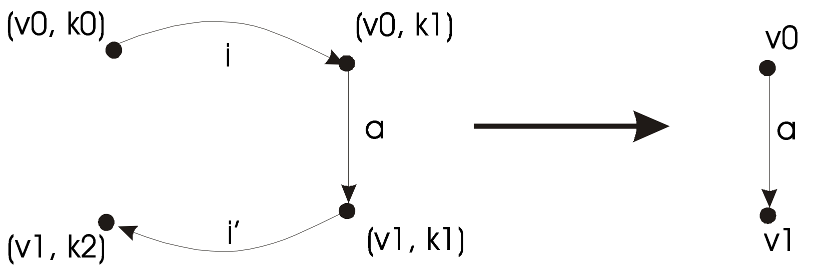

Fig. 4. Examples of wayfinding and action graphs

The action structure within the wayfinding graph represents explicitly the choices that are available during the wayfinding process, and it is often useful to consider this separately from the knowledge component. This is achieved formally by taking an appropriate projection of the wayfinding graph. The *action graph* is derived from the wayfinding graph by amalgamating all the nodes labeled by the same view component into a single node, and eliminating the knowledge components that label the nodes and the edges labeled by information affordances. The left diagram in figure 4 shows an example of a small wayfinding graph with four nodes and three edges, and on the right is its projection as an action graph with two nodes and one edge. In the example, the edges of the wayfinding graph labeled by information affordances *i* and *i'* are eliminated in the action graph, and nodes labeled with (*v0*, *k0*) and (*v0*, *k1*) are amalgamated into the single node *v0* (similarly for (*v1*, *k1*) and (*v1*, *k2*)).

If we are interested in the state of knowledge of a person at different stages in the wayfinding process, then this may also be derived from the wayfinding graph. However, a little care is required here, as knowledge is not just dependent upon the viewpoint. It might be the case, for example, that the person returns to a viewpoint previously visited having gone to look more closely at a map or explore partly a path. In this case, it is likely that the viewpoint will be revisited with increased knowledge.

5 Formal Representation of Wayfinding in a Built Environment: Case Study

In this section we demonstrate the formal model of the process of wayfinding by applying it to a subtask of finding one's way from the check-in counter to a specific gate in an airport, i.e., moving through passport control. This is a specialization of the case study presented in section 2.

5.1 Description of Subtask

The subtask used to demonstrate the formal model is "moving through passport control." The wayfinder stands in front of passport control and has to move through it in order to get closer to the goal. After moving through passport control the wayfinder faces a decision point with three views and three possible path continuations (Figures 5, 6).

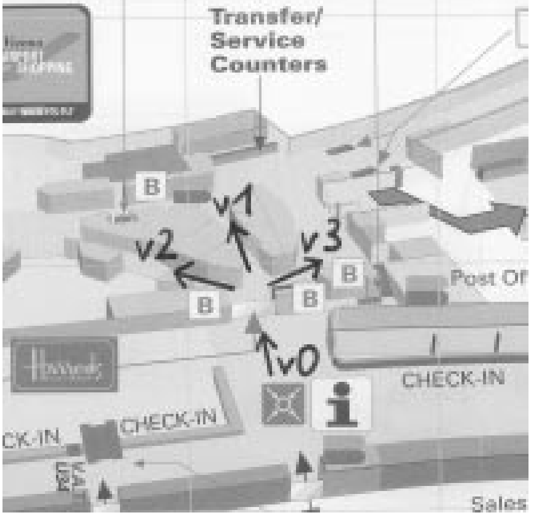

Fig. 5. Moving through passport control at Vienna International Airport

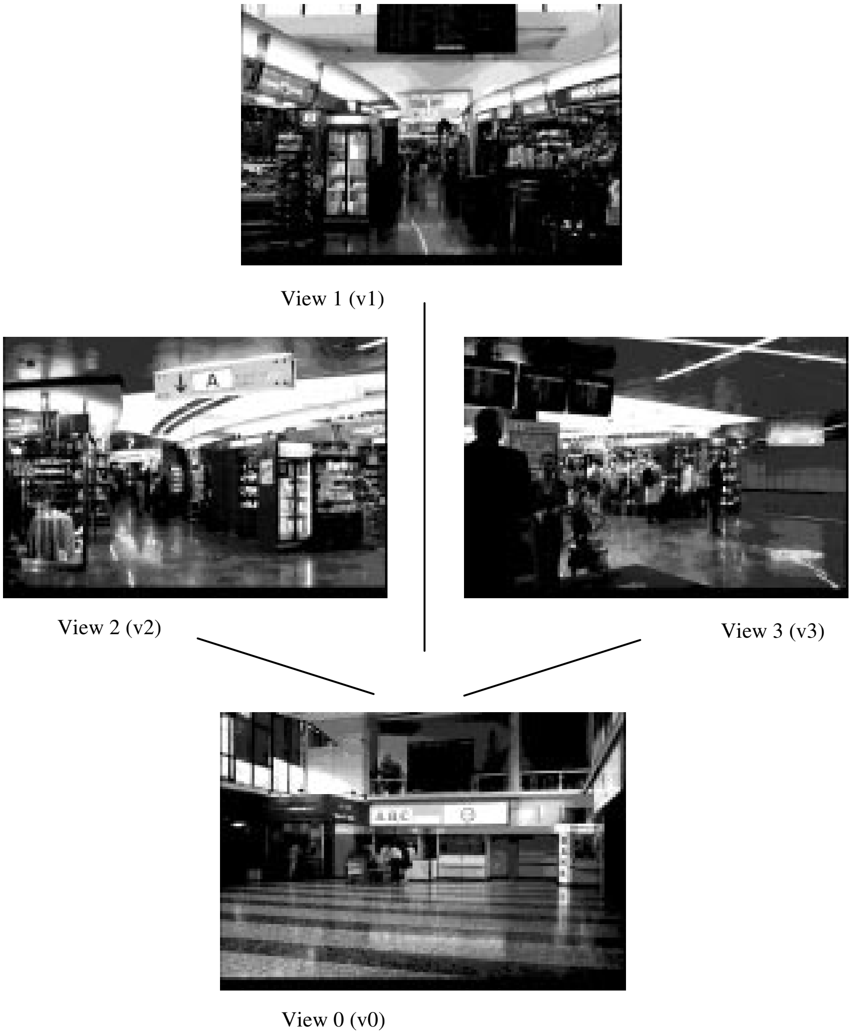

Fig. 6. Moving through passport control at Vienna International Airport (views 0, 1, 2, 3)

5.2 Deducing Affordances from Image-Schematic Descriptions

The first step is to deduce the information and action affordances from image-schematic descriptions. We use transcripts and extracted image schemata from the case study described in section 2. As an example we give one transcript and the extracted image schemata for the view v0 in front of passport control (Table 2).

Table 2. Transcript and extracted image schemata for the view v0 in front of passport control

Transcript	*Extracted Image Schemata*
"I come out in a big taller area."	IN_CONTAINER(I,area),MORE_THAN_IN(area,previous area,height);
"I see an "A, B, C"-gate that says it's passport control."	LINK(I,gate),LINK(I,"A,B,C"), LINK(I,"passport control"), MATCHING(gate,passport control);
"The yellow sign stands out against the rest of the airport signage."	LINK(I,yellow sign), ATTRACTED_BY(I,PART_OF_WHOLE (yellow sign,airport signage));
"The "A" and "B" and "C" are prominent black on white."	ATTRACTED_BY(I,"A,B,C"), ON_SURFACE(black letters,white ground);
"It doesn't say "departures" in that direction."	NO_LINK(I,"departures");
"I see an "A, B, C"-sign in the other direction off to the right."	LINK(I,RIGHT_OF(sign,unspecified object)),LINK(I,"A,B,C");
"I go forward and queue up for passport control."	IN_FRONT_OF(PATH(I,NEAR_FROM(I, passport control)),I), ON_SURFACE(I,floor);
"I go through passport control and head to the gates in the A-B-C-area."	PATH_ALONG(I,gates,CONTAINER (passport control)), IN_CONTAINER(gates,A-B-C-area);

Table 3. Information and action affordances for view v0 in front of passport control

x	*Ix*	*Ax*
IN_CONTAINER(I,area)		Move around the area [a1]. Leave the area [a2].
LINK(I,"A,B,C"-gate) = LINK(I, passport control)	There is a way to gates A, B, C [i1]. The "A,B,C"-gate is passp. control [i2].	Go through the "A,B,C"-gate and passport control [a3].
ATTRACTION(sign) + ATTRACTION("A,B,C")	This is important information [i3].	
NO_LINK(I,"departures")	Information is missing [i4].	Look for "departures" [a4].
LINK(I,other "A,B,C"-sign)	There is a way to gates A, B, and C [i5].	
PATH(I,passport control)	This path is the way to passport control [i6].	Go to passport control and queue up [a5].
PATH_ALONG(I,gates,passport control)	The path through passport control is to the gates [i7].	Go to the gates through passport control [a3].
CONTAINER(passport control)		Enter passport control [a6]. Leave passp. control [a7].
IN_CONTAINER(gates,A-B-C-area)	These gates are in the A-B-C-area [i8].	

According to section 4.1 we can now deduce the information (Ix) and action (Ax) affordances from the image-schematic description (Table 3). Information and action affordances for the rest of the views of the subtask are deduced in the same way (Tables 4, 5, 6).

Table 4. Information and action affordances for view v1 (duty-free area after passport control)

Ix	*Ax*
	Move around the duty-free area [a8].
	Leave the duty-free area [a9].
There is a way to gates B and C [i9].	Go to gates B and C [a10].
There is information about the airport layout and flight information [i10].	Move closer to get precise information [a11].
There are shops [i11].	Buy goods [a12].
The shops are important [i12].	

Table 5. Information and action affordances for view v2 (duty-free area after passport control)

Ix	*Ax*
There are shops [i13].	Buy goods [a13].
There is a way to gates A that goes down the aisle [i14].	Go down the aisle to gates A [a14].
The aisle cannot go very far [i15].	
I do not know where the end of aisle is [i16].	

Table 6. Information and action affordances for view v3 (duty-free area after passport control)

Ix	*Ax*
There are many shops [i17].	Buy goods [a15].
There is a way to gates A and C [i18].	Go to gates A and C [a16].
There is subdued flight information [i19].	Move closer to see full information [a17].

5.3 The Wayfinding Graph Applied to the Subtask

Figure 7 shows the action graph for this example. The wayfinder starts at view *v0*, outside passport control, and, having gained knowledge from that view, takes one of the actions *a1* to *a4* to move to a new view. Those views outside the scope of this discussion are indicated in the figure by "?". Views immediately following passage through passport control are presented to the observer in different orientations but at the same location. These three views, *v1*, *v2* and *v3*, are encapsulated into a single "hypernode." Actions resulting from these views either lead to unknown views outside the scope of consideration in this case study, or to one of the views *v4*, *v5* and *v6*, further along the path to a gate.

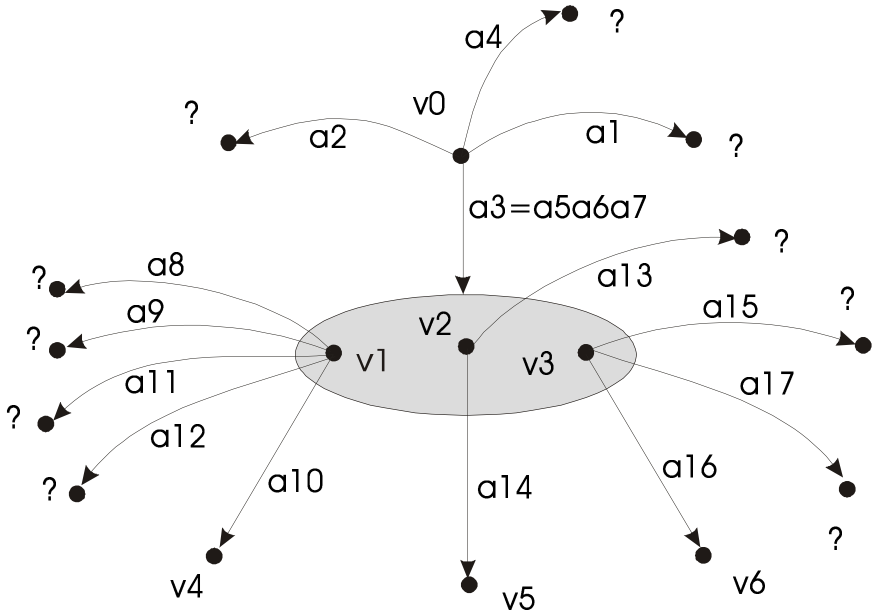

Fig. 7. Action graph applied to the subtask "moving through passport control"

Due to their number, the knowledge transitions in the wayfinding graph are not discussed here in full. To illustrate the idea, knowledge is gained by observations of information affordances of objects in scope of the view. It is assumed that the wayfinder has some level of deductive capability (e.g., deductively complete with respect to first order logic). At the outset, information affordances *i1* – *i8* are presented to the wayfinder providing fairly convincing evidence of an appropriate path to and through passport control leading to gates A, B, and C, and thus to the goal. With this knowledge, the wayfinder might decide to take action *a3* which is composed of *a5* followed by *a6* and *a7*, to progress to views *v1*, *v2,* and *v3*. Further information then guides the decision of what further action should be taken.

6 Conclusions and Future Work

In this paper we presented a formal model of the process of wayfinding in built environments. The model integrated elements of people's perception and cognition (i.e., image schemata and affordances), therefore focusing on how people make sense of their wayfinding environment. Starting with imperfect observations of space, the wayfinder derives incomplete and imprecise knowledge, and based on such knowledge takes an action. Actions lead to further observations and knowledge and, recursively to further actions until the goal is reached. We applied the formal framework to a subtask of finding one's way from the check-in counter to the gate in an airport to show the applicability of the model, using a wayfinding graph.

Our work showed that it is possible to provide a formal framework of the process of wayfinding that integrates parts of people's perception and cognition with information and possibilities for action afforded by the wayfinding environment. The wayfinding graph provides a discrete, dynamic model of knowledge and action as the wayfinding process progresses. Such a model, based on transitions within a finite graph, is computationally tractable, and allows computer simulations of wayfinding that take account of both "knowledge in the world" and "knowledge in the head." The model is of course only an approximation to the real process of human wayfinding, and further work is required to determine how closely it approximates to wayfinding in the real world. For example, color of signage and individual wayfinding criteria such as minimizing travel time or minimizing stress [12] might be additional factors that need to be built into the model.

Further notes for future work:

1. In the current model the logic is monotonic, because knowledge never decreases as the navigation process progresses. In real applications knowledge might decrease, due to confusion, information overload, or just forgetting. Thus, a non-monotonic logic is required to model the activity more accurately.
2. The model needs to be implemented in order to analyze performance and computational cost.
3. Image schemata are controversial because it is difficult to prove the existence of these mental patterns. Future work is required to bring further enlightenment to this idea.
4. More research on the relation between image schemata and affordances will be necessary. We used semantic connotation to deduce affordances from image schemata. Future work is required to make a formal connection between the two.
5. As the literature on wayfinding models does not discuss important features like "being lost", there are no descriptions of negative affordances such as "getting lost." However, it is important to find out about these negative affordances. If their causes—which are highly correlated to the causes of human (wayfinding) errors [26]—could be found, it could in many cases be possible to alter the design of a particular space to get rid of its negative affordances.

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