HUMAN WAYFINDING IN UNFAMILIAR BUILDINGS: A SIMULATION WITH A COGNIZING AGENT

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Existing cognitively based computational models for wayfinding focus primarily on the exploration of mental representations rather than the information needs for wayfinding. It is important to consider *information needs* because people trying to find their ways in unfamiliar environments do not have a previously acquired mental representation but depend on external information. The fundamental tenet of this work is that all information must be presented to the wayfinder at each decision point as "knowledge in the world."

Simulating people's wayfinding behavior in a cognitively plausible way requires the integration of structures for information perception and cognition in the underlying model. In this work we use a cognizing agent to simulate people's wayfinding processes in unfamiliar buildings. The agent-based model consists of two tiers: simulated states of the environment and simulated beliefs of the agent. The agent is modeled with state, an observation schema, a specific wayfinding strategy, and commonsense knowledge. The environment is modeled as a graph, where nodes represent decision points and edges represent lines of movement.

The *perceptual wayfinding model* integrates the agent and its environment within a "Sense-Plan-Act" framework. It focuses on knowledge in the world to explain actions of the agent. The concepts of affordance and information are used to describe the kinds of knowledge the agent derives from the world by means of visual perception. Affordances are possibilities for action with reference to the agent. Information is necessary for the agent to decide which affordances to utilize. During the navigation process the agent accumulates beliefs about the environment by observing task-relevant affordances and information at decision points. The utilization of a "go-to" affordance leads the agent from one node to another where it is again provided with percepts. A successful navigation corresponds to the agent's traversal from a start to a goal node.

The proposed formal specifications of the agent-based model can be used to simulate people's wayfinding behavior in spatial information and design systems in a cognitively plausible way. Such simulation helps to determine where and why people face wayfinding difficulties and what needs to be done to avoid them. The case of wayfinding in an airport, in which the signage in the airport is tested, is employed to demonstrate the perceptual wayfinding model.

1. INTRODUCTION

Wayfinding and orientation form integral parts of people's daily lives. We have to find our ways through cities, through buildings, along streets and highways, etc. Many times the environment to be navigated is unfamiliar: People are there for the first time and have to find a goal without the help of a previously acquired mental map. They depend on external information or what Norman (1988) calls *knowledge in the world*. Such knowledge resides in the environment and is communicated through signs, guidance systems, and architectural clues. In many cases people find it difficult to perform wayfinding tasks in an unfamiliar environment because they are not provided with adequate knowledge in the world. The main reason for environments being too complex to facilitate wayfinding is a deficiency of clues (Raubal and Egenhofer 1998). They either lack sufficient wayfinding information or their architectures are badly designed and therefore not readable. We all know the stressful and sinking feeling when one gets lost in an airport, a large office building, or on a university campus.

Previous research focused on the development of computational models that simulate wayfinding in familiar environments. Route-planning tasks are solved with the help of a simulated cognitive map. During wayfinding in an unfamiliar environment people cannot use an internal map but have to rely on other sources to satisfy their *information needs* (Gluck 1991). We are interested in how people immediately make sense of the information presented to them at various decision points in the environment and how they proceed further during a wayfinding task using the provided information. This means looking at the wayfinding process itself instead of looking at the representation.

This work proposes a cognizing agent to simulate people's wayfinding behavior in unfamiliar buildings based on knowledge in the world. We therefore call it a model for *perceptual wayfinding*. The agent gains knowledge about the building through visual perception of sign information and affordances at decision points. The concept *affordance* comes from ecological psychology; it is what an object, an assemblage of objects, or an environment enables people to do. An internal observation schema directs the agent's perception. We do not model the process of perception itself, but inspect the kind of information and affordances the agent needs at each decision point to reach its goal. Neither the ability to learn nor a lasting cognitive-map-like representation of the environment is involved in deciding upon and taking an action. The agent's decisions and actions are based on a wayfinding strategy and commonsense reasoning and are also guided by the agent's observation schema. Based on knowledge in the world the agent takes a sequence of actions until the wayfinding task is completed. This process is represented through a transition graph consisting of nodes (decision points in the environment) and edges (paths between such points). A successful navigation of the building corresponds to the agent's traversal of the graph ending at a goal node.

The main question in this research is the following: Is it possible for a cognizing agent to reach a wayfinding goal based on knowledge in the world only—i.e., are there enough signs at every decision point so that the agent can reach its goal? We will answer it with regard to a specific case study used to demonstrate our approach: The agent simulates a passenger at Vienna International Airport and has to perform the task of finding the way from the check-in counter to a specific gate. The question is of high practical importance because people need to find their ways in a spatial environment without the help of a map. For example, for many public buildings, maps are not available. In emergency situations such as fires, wayfinding based on knowledge in the world can make the difference between life and death, because people must find the emergency exits as quickly as possible. Signs showing the way to the next emergency exit are therefore required at every decision point.

With the use of simulation tools, such as the one presented in this work, wayfinding tasks can be tested before the actual construction of a built environment. It is possible to determine where people face wayfinding difficulties, why they face them, and how wayfinding information and design have to be changed to avoid such difficulties. Simulation with cognizing agents in future spatial information and design systems will allow testing of wayfinding tasks in a cognitively plausible way because they integrate people's perceptual and cognitive concepts—e.g., affordances and schematic structures.

In section 2 we relate our work to human spatial cognition, human wayfinding research, and other computational wayfinding models. Section 3 presents the modeling concepts used here—agents and affordances. A formal model for agent-based wayfinding simulation is developed in section 4. Starting from its grounding in people's experiences we explain our considerations for the design of the model. We then describe the structure and representation of the cognizing agent and its environment. The process model for wayfinding and its use to perform analyses during wayfinding simulation are also illustrated. An application of the formal model to simulate the task of finding one's way from the check-in counter to a specific gate in an airport is shown in section 5. Section 6 presents results and conclusions, and suggests directions for future work.

2. WAYFINDING RESEARCH RELATED TO THIS WORK

Finding one's way through a building depends on a variety of elements. In this section we refer to human spatial cognition and review human wayfinding research and computational wayfinding models.

2.1 Human spatial cognition

Knowledge about human spatial cognition is important for explaining and predicting people's behavior in geographic space (Mark 1997). Human spatial cognition is a part of the interdisciplinary research area of cognitive science. Researchers from many academic disciplines, such as psychology, linguistics, anthropology, philosophy, and computer science investigate about mind, reason, experience, and people's conceptualizations of the world in which they live (Lakoff 1987). In particular, cognitive science deals with the study of human intelligence in all of its forms, from perception and action to language and reasoning. The exercise of intelligence is called cognition (Osherson and Lasnik 1990). The agent specified in this work, perceives, decides, and acts; we therefore call it *cognizing agent*.

Mark *et al.* (1999) present a hypothetical information flow model for spatial and geographical cognition, which consists of four stages: acquisition of geographical knowledge, mental representations of geographical knowledge, knowledge use, and communication of geographical information. This work focuses on two of them—modeling the agent's acquisition of affordances and information from its environment and using such knowledge in the world to accomplish a wayfinding task. Furthermore, the stage of action in the environment is added.

Spatial cognition refers to both the perceptual and conceptual processes involved in understanding the physical environment. Therefore, wayfinding theories need to integrate a link between perception and cognition if they want to serve as plausible accounts of people's everyday experience (Allen 1999).

2.2 Human wayfinding

Human wayfinding research investigates the processes that take place when people orient themselves and navigate through space. Theories try to explain how people find their ways in the physical world, what people need to find their ways, how they communicate directions, and how people's verbal and visual abilities influence wayfinding. Allen (1999) and Golledge (1999) describe wayfinding behavior as purposeful, directed, and motivated movement from an origin to a specific distant destination that cannot be perceived directly by the traveler. Such behavior involves interactions between the traveler and the environment. Human wayfinding takes place in large-scale spaces (Downs and Stea 1977; Kuipers 1978). Such spaces cannot be perceived from a single viewpoint therefore people have to navigate through large-scale spaces to experience them. Examples for large-scale spaces are landscapes, cities, and buildings. Wayfinding tasks can be categorized according to their functional goals. Allen (1999) distinguishes between travel with the goal of reaching a familiar destination, exploratory travel with the goal of returning to a familiar point of origin, and travel with the goal of reaching a novel destination. Our work focuses on the task of finding one's way to a novel destination in an unfamiliar environment. In such situations, people have to rely on symbolic spatial information communicated to them through the environment. Key processes for this type of communication relate to abilities such as matching real-world features against knowledge schemas (Raubal 1997) of those features and understanding the symbols commonly used to represent real features (Golledge 1999).

People's spatial abilities depend mainly on the following four interactive resources: perceptual capabilities, fundamental information-processing capabilities, previously acquired knowledge, and motor capabilities (Allen 1999). These abilities are a necessary prerequisite for people to find a way from an origin to a destination. They are needed to use environmental information, to use representations of spatial knowledge, and to move through the environment. Wayfinding in a building is mainly concerned with the interactions between a mobile observer and large stationary objects. The foundation for this class of spatial abilities is sensitivity to perceptual information. Examples are obstacle avoidance and path integration. As for the spatial abilities, the cognitive abilities also depend on the task at hand. Finding one's way in a street network (Timpf *et al.* 1992; Car 1996) uses a different set of cognitive abilities than navigating from one room to another in a building (Gärling *et al.* 1983; Moeser 1988).

The literature on human wayfinding performance discusses empirical results of how people find their ways. Investigations are based on collecting individuals' perceptions of distances, angles, or locations. Lynch's (1960) principles for city design are regarded as the foundation for human wayfinding research. Weisman (1981) identified four classes of environmental variables that influence wayfinding performance in built environments: visual access; architectural differentiation; signs and room numbers to provide identification or directional information; and plan configuration. Other researchers (Gärling *et al.* 1983, 1986; O'Neill 1991a, b) confirmed his results. Seidel's (1982) study at the Dallas/Fort Worth Airport showed 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.

Research on people's wayfinding performance helped to establish practical guidelines on how to design public buildings to facilitate wayfinding. Arthur and Passini (1990, p. A-1) introduced the term *environmental communication* (i.e., "transfer of orientation, wayfinding (direction), and other information within the built environment by means of signs and other communications devices or architectural features to enable people to reach destinations"), arguing that the built environment and its parts should function as a communication device. They mention two major aspects regarding the understanding of buildings: a spatial aspect that refers to the total dimensions of the building and a sequential aspect that considers a building in terms of its destination routes. Destination routes should eventually lead to so-called destination zones. These are groupings of similar destinations within buildings into clearly identifiable zones (Arthur and Passini 1992). In order to facilitate wayfinding to such destination zones the circulation system should be of a form people can easily understand.

Our proposed wayfinding model is based on people's visual access to affordances and information at decision points. It focuses on signage for directional information and its influence on wayfinding performance. The grouping of similar destinations into destination zones plays an important role for our case study: Gates are grouped within gate areas, for example, gates C51, C52, C53, etc. are all part of gate area C. The agent uses such hierarchical knowledge to decide if its goal information matches any of the perceived information from signs.

2.3 Computational models for wayfinding

Cognitively based computational models simulate a wayfinder that can solve route-planning tasks with the help of a cognitive-map-like representation. The focus of these models is to find out how spatial knowledge is stored and used, and what cognitive processes operate upon it. One distinguishes between computational process models where cognition is conceptualized as sets of rules acting on symbolic representations, and biologically inspired models that model cognition through the use of lower level, physiologically plausible mechanisms.

The TOUR model is considered the starting point for a computational theory of wayfinding (Kuipers 1978). It is a model of spatial knowledge whose spatial concepts are based mainly on observations by Lynch (1960) and Piaget and Inhelder (1967). With the TOUR model Kuipers simulates learning and problem solving while traveling in a large-scale urban environment. His main focus of attention is the cognitive map in which knowledge is divided into routes, a topological street network, relative positions of two places, dividing boundaries, and containing regions. This knowledge is represented through environmental descriptions, current positions, and inference rules that manipulate them. Routes are described as sequences of View-Action pairs. Because TOUR copes with incomplete spatial knowledge of the environment, it learns about it by assimilation of observations into the given structure. A subsequent application to the TOUR model utilizes an approach to robot learning based on a hierarchy of types of knowledge of the robot's senses, actions, and spatial environment (Kuipers *et al.* 1993).

Several other cognitively based computational models, such as TRAVELLER (Leiser and Zilbershatz 1989), SPAM (McDermott and Davis 1984), and ELMER (McCalla *et al.* 1982), simulate learning and problem solving in spatial networks. The program ARIADNE (Epstein 1997) learns facilitators and obstructers for pragmatic two-dimensional navigation. NAVIGATOR (Gopal *et al.* 1989; Gopal and Smith 1990) integrates concepts from both cognitive psychology and artificial intelligence. It represents basic components of human information processing, such as filtering, selecting, and forgetting. In this model, cognitive processes relating to spatial learning and using such knowledge for navigation complement two views of a suburban environment—an objective and a subjective one. The cognitive map is modeled through a hierarchical network consisting of nodes, links, subnodes, and sublinks. The computational process model analyzes retrieval of spatial knowledge and wayfinding by using the following measures: see if the goal is reached; amount of time taken to reach the goal; quality of pattern matching between information in memory and goal information; and errors in navigation and search strategies. O'Neill (1991) presents a model of spatial cognition and wayfinding that is built upon the biological approach. NAPS-PC builds an artificial neural network of choice points and connecting paths from a textual list of places, preserving their topological relationships. A search for a route starts by stimulating the start and goal nodes to their maximum activity. The activity propagates from these two nodes through the network until it intersects. Nodes in-between that get activated function as subgoals during the search. The simulation models processes of people who already have knowledge of the environment during wayfinding tasks.

The focus of these computational models lies primarily in the creation and exploration of the cognitive map; they largely neglect the processes of how people immediately perceive and assign meaning to their spatial environments as they navigate through them. For example, Kuipers' TOUR model completely ignores sensory impressions. Golledge (1992) mentions the possibility of spatial knowledge not being well described by existing theories or models of learning and understanding and, therefore, calls for more research on human understanding and use of space.

3. MODELING CONCEPTS

The work presented here is based on agent theory and Gibson's theory of affordances. In the following we briefly introduce the concepts used later.

3.1 Agents

Various definitions of what an agent is can be found in the literature. An agent can be seen as a technical concept, a metaphor, or a design model (Gilbert *et al.* 1995; Nwana and Ndumu 1996). In this work we use *agent* as a conceptual paradigm for the simulation of people's wayfinding behavior in unfamiliar buildings.

Agents have been mainly dealt with in artificial intelligence but have recently also gained popularity in other fields such as geography (Frank 2000). In general, an agent can be anything that can perceive its environment through sensors and act upon that environment through effectors (Figure 1) (Russell and Norvig 1995). More specifically, agents are considered computer systems that are situated in an environment and can act autonomously (Wooldridge 1999). The main difference between agents and objects is that agents have a stronger notion of autonomy, because objects do not themselves have control whether one of their methods to act is executed or not. Objects also lack flexibility. Agents must be distinguished from expert systems as well. Expert systems are disembodied—they do not interact directly with an environment but give advice to a third party—, lack the ability to cooperate with other agents (Wooldridge 1999), and do not learn (Nwana and Ndumu 1996).

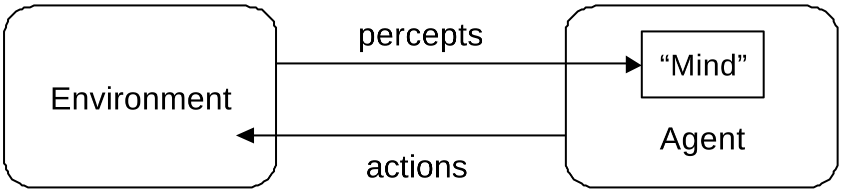

Figure 1: Agents interact with their environment—based on Russell and Norvig (1995).

Agents can be represented as functions that map percepts to actions. Abstract models of agents distinguish between purely reactive agents, agents with subsystems for perception and action, and agents with state (Wooldridge 1999). These abstract models can be implemented in different ways, depending on how the decision making of the agent is realized (Bryson 2000).

3.2 Affordances

Affordances are a concept from ecological psychology. This discipline studies the information transactions between living systems and their environments, especially with regard to the perceived significance of environmental situations for the planning and execution of purposeful behaviors (Shaw and Bransford 1977). The world is seen as the information source for perception and action. Ecological psychology denies that nature communicates to us in the form of data inputs that must be translated by a phalanx of cognitive homunculi into a more readable form: We extract meaning directly through our perceptual systems, therefore knowing is a direct process.

One of the proponents of ecological psychology was J. J. Gibson, who investigated how people visually perceive their environment (Gibson 1979). According to Gibson, the environment consists of a medium, substances, and surfaces. We move in a medium—of light, sound, and odor—in which there are points of observation and lines of locomotion. The substances differ in chemical and physical composition, and are structured in a hierarchy of nested units. The medium is separated from the substances of the environment by surfaces. Gibson describes the process of perception as the extraction of invariants from the stimulus flux. Surfaces absorb or reflect light and Gibson's radical hypothesis is that the composition and layout of surfaces constitute what they afford. Affordances are therefore specific combinations of the properties of substances and surfaces taken with reference to an observer. These invariant compounds are specified in ambient light and detected as units. Ambient light has structure and therefore information.

Gibson was later criticized for grounding his theory only on perception and neglecting processes of cognition. Lakoff (1987, p. 216) states "the Gibsonian environment is not the kind of world-as-experienced that is needed in order to account for the facts of categorization … his account only deals with individual phenomena, not categories of phenomena." Norman (1988) investigated affordances of everyday things, such as doors, telephones, and radios, and argued that they provide strong clues to their operation. He adapted Lakoff's view and recast affordances as the results from the mental interpretation of things based on people's past knowledge and experiences. Gaver (1991) stated that a person's culture, social setting, experience, and intentions also determine her perception of affordances. Similarly, Rasmussen and Pejtersen (1995) have pointed out that modeling the physical aspects of the environment provides only part of the picture. "The framework must serve to represent both the physical work environment and the 'situational' interpretation of this environment by the actors involved, depending on their skills and values" (Rasmussen and Pejtersen 1995, p. 122). This can be broken into three relevant parts, the mental strategies and capabilities of the agents, the tasks involved, and the material properties of the environment.

4. A FORMAL MODEL FOR AGENT-BASED WAYFINDING SIMULATION

In this section we develop a formal agent-based model for wayfinding in unfamiliar buildings. We first give attention to design considerations to assure that the agent-based system is firmly grounded. Such grounding is a necessary requirement to model the agent's behavior in a cognitively plausible way. We then describe the conceptual model, which consists on the one hand of the agent and its environment, and on the other hand of the wayfinding process represented within a Sense-Plan-Act framework. The conceptual model is formalized as an algebraic structure.

4.1 Design considerations

When developing a tool to simulate human behavior in space, one needs to certify that the underlying theory of the process is firmly grounded in people's real world experiences. We used empirical data from human subject testing concerning wayfinding in airports to construct the ontology and epistemology for the agent and its environment (Raubal to appear). This was done by using an ecological approach. The ontology consists of categories of substances that occur in an airport. The two main categories are *cognizing agents* (travelers, airport staff, etc.)

and *non-cognizing objects* (signs, counters, gates, etc.). The epistemology focuses on the agent's knowledge and beliefs, which are modeled through affordances. A distinction is made between *physical*, *social-institutional*, and *mental affordances*. We thereby supplement Gibson's theory of perception with elements of cognition, situational aspects, and social constraints—based on the various critics with regard to his theory (section 3.2).

Following the separation between ontology and epistemology, our model for agent-based wayfinding simulation is two-tiered (Frank 2000a). On the one hand, we consider states of the real-world environment, which are mapped to simulated environment states. On the other hand, we assume beliefs of a person about the environment. These beliefs are the result of perception and are mapped to simulated beliefs of the agent. Accordingly, percepts and actions in the real world are mapped to simulated *percepts'* and simulated *actions'* (Figure 2). The two-tiered approach allows for integration of people's incomplete and imprecise knowledge derived from imperfect observations of space (Raubal and Worboys 1999; Worboys 1999). It is also possible to model the perception of parts of the environment.

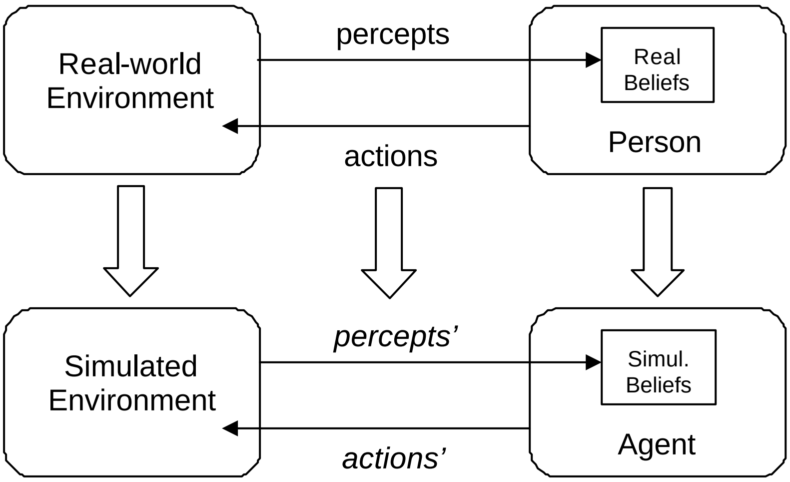

Figure 2: Mapping from real world to simulation within a two-tiered model.

Simplifying assumptions have to be made during the design of the agent-based model to achieve computational tractability. Gibson's idea that the medium consists of points of observation and lines of locomotion serves as a motivation to model the wayfinding environment through a graph of nodes and edges. We represent one cognizing agent, which has to solve a route-finding task. Non-cognizing objects are modeled on the perceptual level through affordances and information. In particular, we consider signs, gates, gate areas, decision points, and paths. The most relevant physical affordance for wayfinding simulation is a path's affordance to move along it. We represent it explicitly in the model as "go-to" affordance. Its utilization leads the agent from one node to another. Other physical affordances, such as a sign's affordance to reflect light, a decision point's affordance to look for a clue, or a doorway's affordance to go through, are implicit in the model and allow for the agent's perception and locomotion. Social-institutional affordances for the agent are inherent in the model through the semantic scope of the task in the given social setting—wayfinding in an airport. Furthermore, we assume that the agent is able to utilize affordances such as to read and extract information from a sign. Mental affordances are represented through the agent's decision process. Sign information affords being matched with the agent's goal information, paths afford being selected, and decision points afford searching, orienting, and deciding how to proceed. These processes are explicitly included in the model.

We use algebraic specifications to formalize the model. Algebraic specifications are the link between the conceptual model and its implementation. Their purpose is to formally describe the behavior of objects and fix the meaning of the conceptual model. Algebraic specifications of the model are written in the functional programming language Haskell (Hudak *et al.* 2000). Definitions are built in the form of functions, which are evaluated by a computer. Algebraic specifications written in Haskell are executable and can be tested as a prototype. The signatures given here are for illustration purposes. The complete code including data representations can be downloaded from ftp://ftp.geoinfo.tuwien.ac.at/raubal/wayfindSimulCode.ZIP.

4.2 The cognizing wayfinding agent

The cognizing wayfinding agent specified in this work is not capable of total autonomous action because it does not have the means to learn from experience. It is rather modeled as a rational agent trying to maximize its performance measure, i.e., finding the way to a goal in the airport. This is done on the basis of knowledge in the world and a necessary minimum of knowledge in the head. The structure of this agent is similar to that of a goal-based agent (Russell and Norvig 1995). Goal-based agents need the current state description and goal information. The agent combines this with information about results of possible actions and then chooses actions to achieve the goal. Goal-based agents are more flexible with respect to reaching different destinations: If a new destination is specified, then the goal-based agent comes up with new behavior.

The main components of the cognizing wayfinding agent are its observation schema, the agent's state, a wayfinding strategy, and commonsense knowledge (Figure 3). Successful interaction of these components is necessary during the wayfinding task so that the agent can reach its goal.

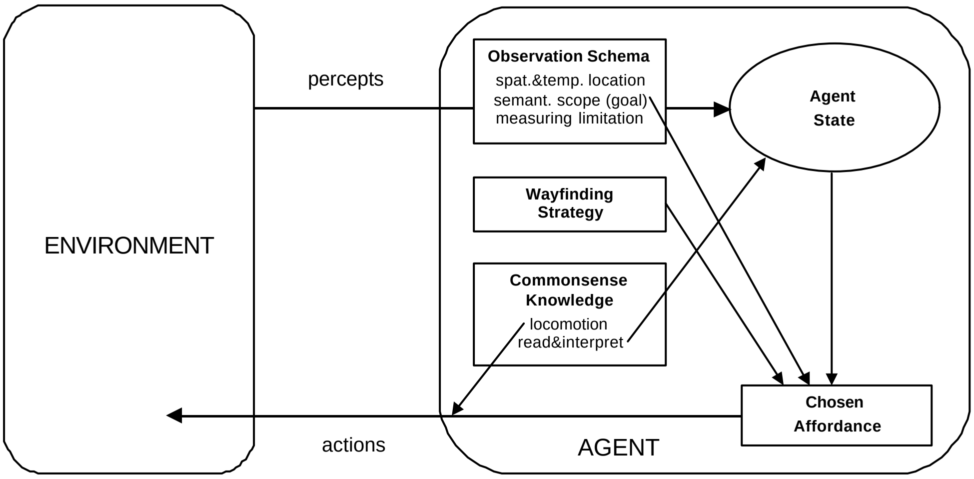

Figure 3: Interaction of components of the cognizing wayfinding agent.

The *observation schema* is the framework and context in which the agent's observations are made (Raubal and Worboys 1999; Worboys 1999). We define it based on Neisser's (1976) schema definition as internal to the agent and directing the agent's perception of affordances and information from the environment. The observation schema includes the spatial and temporal location at which observations are made, the spatial and semantic scope of the observations according to the given task and goal, and possible limitations of measuring instruments. This work does not focus on the process of perception itself, therefore we assume that the cognizing agent's sensors are not limited and lead to precise and complete observation instances.

Observations result in beliefs of the agent about some state of the environment at a specific spatial and temporal location. The cognizing wayfinding agent maintains an internal *state* (comparable to people's short-term memory) where all beliefs are kept until the agent moves to another decision point and represents another part of the environment. We model the agent's beliefs about the environment as perceived affordances and information. The knowledge available in the agent's state contains therefore the set of perceived affordances from which one or more are later chosen and utilized as actions.

The agent needs to apply a specific *strategy* to situations where two or more possible ways lead to the goal. Take the following situation from the task of finding gate C54 at Vienna International Airport (Figure 4). The agent stands in front of passport control and has to move through it to get closer to the goal. After moving through passport control, the agent faces a decision point with three possible path continuations. Two of them, the path straight ahead to gate areas A and C, and the path to the right to gate areas B and C, are correct continuations for gate C54. Therefore the wayfinding agent needs a strategy to decide which way to go (the alternative is a random choice).

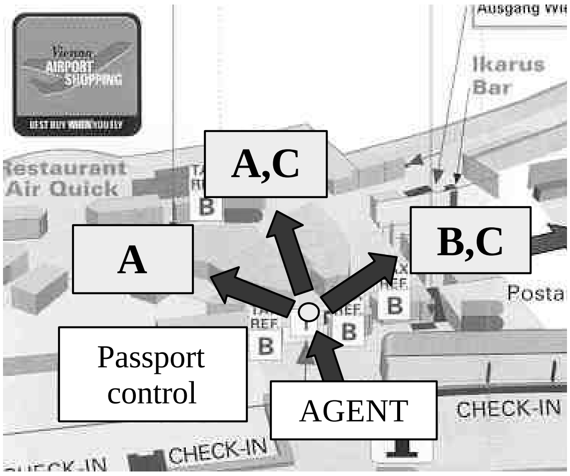

Figure 4: Wayfinding agent in front of passport control at Vienna International Airport.

A strategy contains decision rules that seek a result from all possible ways of making a relevant decision. We include such strategy in the agent's model by taking preferences of the agent into account. This allows for arranging multiple solutions to the continuation of the wayfinding process at a decision point in sequence according to clearly established criteria (Golledge and Stimson 1997). Preferences are modeled as preferred directions within the agent's egocentric reference frame. The reference frame is represented through eight directions, i.e., front, back, left, right, and four directions in-between. We assume that people prefer to continue along a path in directions to their front instead of turning around and going side- or backwards. Figure 5 shows the directions with their corresponding preference values—1 being the highest. This wayfinding strategy is an assumption and needs to be confirmed by empirical human subject testing. In case of a falsification of our hypothesis, preference values can be easily changed without influencing the other components of the agent.

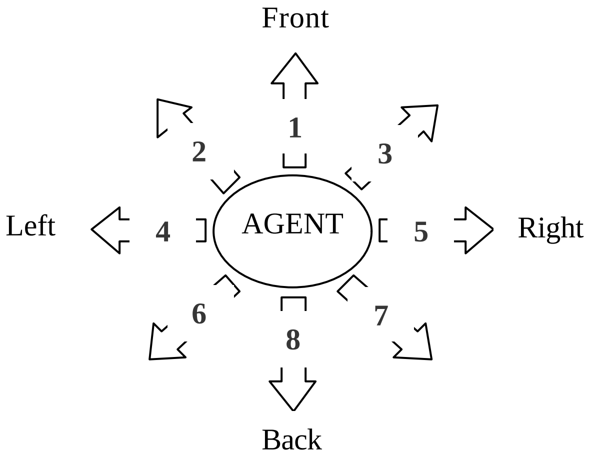

Figure 5: Directions within the agent's egocentric reference frame and preference values.

Starting with people's first experiences with their environment they are establishing knowledge about the world in which they live. This knowledge is needed for everyday activities and called *commonsense knowledge*. We assume that the wayfinding agent has some sort of commonsense knowledge and uses it during the simulation. Such common sense includes the abilities to

- perform acts of locomotion, defined as "coordinated behavior in response to local surrounds" by Montello (2000) who distinguishes between locomotion and wayfinding—a higher-order process involving landmarks, signs, etc.; locomotion is standing upright, avoiding barriers, or heading towards objects;
- read and understand the meaning of what is read; for example, the agent knows about the semantics of "A, B, C" (gate areas A, B, C) and "C54" (gate with the number 54 in gate area C); it also knows what symbols such as an arrow mean—follow the path in the direction of the arrow;

We formally represent the cognizing wayfinding agent as a data type, which is itself constructed from different types.

```
data Agent = Agent AgentId Time Position Goal Preferences AgentState
                          IncomingDir Decision Hist
```

The agent has an identifier (`AgentId`) and is specified for a given moment in `Time` and `Position`. With regard to our case study the agent's `Goal` represents a gate in the airport. The foundation for the agent's wayfinding strategy is formally represented as a list in which every direction within the agent's egocentric reference frame is assigned a value of preference:

```
type Preferences = [(Direction,Preference)]
```

`AgentState` represents the agent's beliefs about the environment as pairs of information (`Info`) and affordance (`Affordance`). We call each individual pair a spatial situation and define the data type `SpatialSit` for it.

```
type AgentState = [SpatialSit]
```

```
data SpatialSit = SpatialSit Info Affordance
```

`IncomingDir` specifies the direction from which the agent enters a decision point. We need the incoming direction to transform the local reference frame of a node into the egocentric reference frame of the agent. This transformation is a prerequisite for applying the agent's wayfinding strategy using preferred directions. The agent's choice to utilize a particular affordance is represented as type `Decision`. Keeping an updated log of the agent's history

(`Hist`) for each point in time allows all perceptions, decisions, and actions of the agent to be reviewed.

4.3 The wayfinding environment

Wayfinding environments in the real world have a high degree of complexity. They are dynamic, continuous, and most often nondeterministic. One needs to apply mechanisms of abstraction to represent a real-world environment in a computer system. We make the following assumptions when mapping the real-world environment to the simulated environment:

- The simulated environment is static and cannot change while the cognizing agent is deciding on an action. This does not have an impact on the correctness of the simulation results because signs and paths do not change that quickly in the real-world environment.
- The number of possible percepts and actions for the cognizing agent is limited, therefore the simulated environment is discrete. This is a necessary supposition to assure that the model stays computationally tractable and allows wayfinding simulations within a formal framework.
- The cognizing agent has access to the complete, accurate, and up-to-date state of the simulated environment at every decision point. We do not investigate wayfinding errors due to imperfect observations of space in this work.

While finding the way from one place to another in the real world, travelers consistently use sensory cues from the environment. Wayfinding clues such as from signs are especially important at decision points where a person has the opportunity to select among different paths. The number of decision points directly influences the difficulty of performing a wayfinding task (Arthur and Passini 1992; Raubal and Egenhofer 1998). Representing the simulated environment through a graph reflects the importance of decision points during wayfinding. Nodes of the graph simulate decision points and have a position and state attached to them. Edges represent transitions between positions and states, and therefore movement of the cognizing agent between decision points.

We formally represent each node as data type `NodeState`, which is constructed from the types `Position`, `State`, and `MatchDirection`. The `State` for each `NodeState` is again defined as a list of spatial situations. The type `MatchDirection` defines a table in which all node positions from where the agent may directly enter a given node are assigned an incoming-direction value within the local reference frame of the given node.

```
data NodeState = NodeState Position State MatchDirection

type MatchDirection = [(Position,Direction)]
```

We can now specify the whole wayfinding environment as a list of all nodes and assign the type `NodeStates` to it.

```
type NodeStates = [NodeState]
```

4.4 The process model for wayfinding

The wayfinding model (Figure 6) integrates the agent and its environment in a Sense-Plan-Act (SPA) framework (Gat 1998). Within the SPA-approach, the agent senses its environment, develops a plan, and acts according to this plan. We represent these three steps through a *see* function, a *decide* function, and an *action* function. The internal schema guides the agent's processes of perception, decision, and action. Information about the task and goal, a wayfinding strategy, and commonsense knowledge are necessary for the agent to perform the task. The task description directs visual perception in such a way that the agent samples only task-relevant affordances and information. The model concentrates on the actual information needs during wayfinding and does not focus on learning a spatial environment. Its fundamental tenet is that all information must be presented at each decision point as knowledge in the world (Norman 1988). We therefore call it a model for *perceptual wayfinding*.

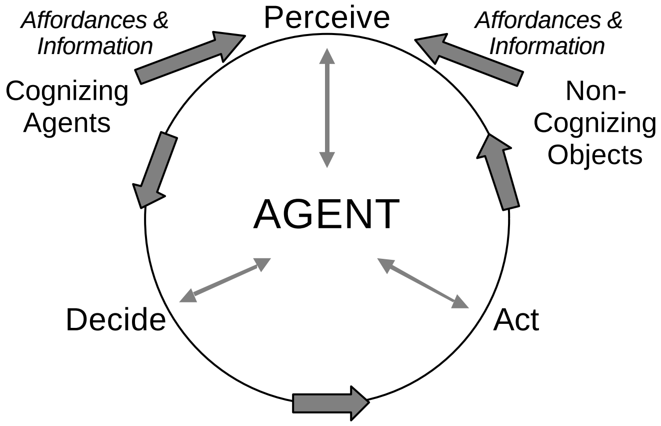

Figure 6: Conceptual process model for wayfinding.

The three main functions of the SPA-approach (`see`, `decide`, `action`) are represented as operations of the class `Agents`. With the `see` function we represent the agent's perception of spatial situations—affordances and information—from the environment. The `decide` function is an internal operation through which the agent comes to the decision of what to do next. First, the agent checks if it has already reached its goal. This is the case when the element in the agent's state matches the agent's goal. If the agent has reached its goal, then the wayfinding task is completed. Otherwise, the agent looks if its goal matches any of the gate-sign information in its state, and if so, the corresponding "go-to" affordance becomes the result of the agent's decision-making process. With more than one piece of gate-sign information matching the goal, the agent decides upon an affordance according to its preferences. The `action` function is used to simulate the agent's utilization of an affordance. Affordances are possibilities for behavior, therefore it is necessary to distinguish between the agent's decision to utilize a particular affordance (the result of the `decide` function) and the agent's actual performance of the action offered by the affordance (the result of the `action` function). Within our specification, the agent can utilize "go-to" affordances. Such action leads the agent to a new node and therefore to a change in its current position. The agent's state becomes empty because we do not focus on aspects of learning. The `see` function needs to be applied again to the agent at the new node to receive input for the agent's state.

The function `wayfind` represents one sequence of Sense-Plan-Act (`see->decide->action`), which specifies the process of the agent moving from one node to another. The graph representing the environment has at least two distinguished nodes, the start node where the wayfinding process begins and the goal node marking the end of the wayfinding process. We can simulate the process of wayfinding by the agent's traversal of the graph from the start state to the goal state. In this work, the cognizing agent is specified separately from the environment. Therefore all changes, such as the change of the agent's position after a move, are represented within the agent. As the environment is static, we do not represent new states of the environment after the agent has performed an operation.

```
class Agents agent where
   see      :: NodeStates -> agent -> agent
   decide   :: agent -> agent
   action   :: agent -> agent
   wayfind  :: NodeStates -> agent -> agent
```

These abstract definitions are independent of any implementation and can be implemented for different types of agents. In this work, we implemented them for the data type `Agent` as defined in 4.2, using also `NodeState` and `NodeStates` as defined in 4.3.

Information helps the agent to choose between various affordances the one(s), which, when utilized by the agent, contribute(s) to reaching its goal. The most important information regarding the task of finding one's gate in an airport comes from gate signs. Our representation of gate signs distinguishes between three types depending on the information content (Figure 7).

1. *Single* content, such as "A" or "C51";
2. *List* content, such as "C52, C53" or "A, B, C, D"; and
3. *Range* content, such as "C54 – C61" or "A – D".

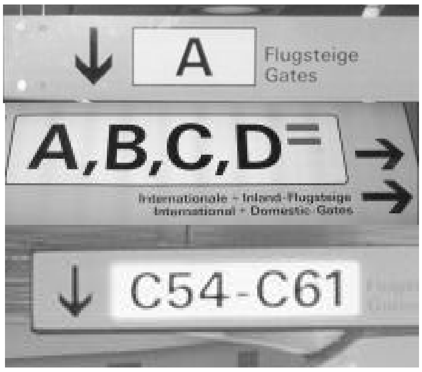

Figure 7: Three different types of gate signs.

This distinction is specified through the data type `GateSign`. The elements of its constructor functions are the data types `GateSignSingle`, `GateSignList`, or `GateSignRange`.

```
data GateSign = GateSign GateSignSingle | GateSign1 GateSignList |
                GateSign2 GateSignRange
```

The function `matchGateSign` allows the agent to evaluate if its goal information (knowledge in the head) matches any of the perceived information from signs (knowledge in the world). This means that based on its goal information (e.g., C54), the agent can decide if a piece of sign information is relevant for reaching the goal (e.g., C) or not (e.g., A). Instances of the function `matchGateSign` are specified for the abstract specification in the class `GateSigns`, and for different types of information content. The function `isTypeAtGate` decides if a gate sign is at the gate or not.

```
class GateSigns gateSign where
  matchGateSign :: Goal -> gateSign -> Bool
  isTypeAtGate  :: gateSign -> Bool
```

4.5 Analysis of the wayfinding simulation

The formal specifications of the agent-based wayfinding simulation allow us to analyze the wayfinding process of the cognizing agent in an unfamiliar building. The result of the agent-based wayfinding simulation is an infinite list of data types `Agent` (one for each time instance). We call this function `historyOfAgent`. Haskell uses a *lazy evaluation* strategy—an argument to a function gets evaluated only if the argument's value is needed to compute the overall result. As a consequence, the use of infinite lists does not lead to infinite computation. Computation of list elements terminates if the agent has reached its goal. If the agent has not reached its goal after a certain number of steps—this number needs to be defined according to the complexity (Raubal and Egenhofer 1998) of the building—the list is cut and can be searched for possible loops the agent is caught in (`findCycle`). This search is based on the function `positionsOfAgent`. Its result is a list of all consecutive positions the agent has reached during the performance of its wayfinding task. The analysis functions `historyOfAgent`, `positionsOfAgent`, and `findCycle` are specified as operations in the abstract class `Agents`.

```
class Agents agent where
  historyOfAgent :: NodeStates -> agent -> [agent]
  positionsOfAgent :: NodeStates -> agent -> [Position]
  findCycle :: NodeStates -> agent -> [Position]
```

5. SIMULATION OF WAYFINDING IN AN AIRPORT

In this section we demonstrate the formal model for agent-based wayfinding simulation by applying it to the task of finding one's way from the check-in counter to a gate at Vienna International Airport. We are interested if the agent is able to reach its goal based on the affordances and information offered at different decision points, and if not, where and why the agent faces wayfinding difficulties, and what can be done to avoid them.

5.1 The wayfinding task

The agent's task is to find it's way from the check-in counter in the departure hall to gate C54. The wayfinding graph representing the agent's wayfinding environment is shown in Figure 8.

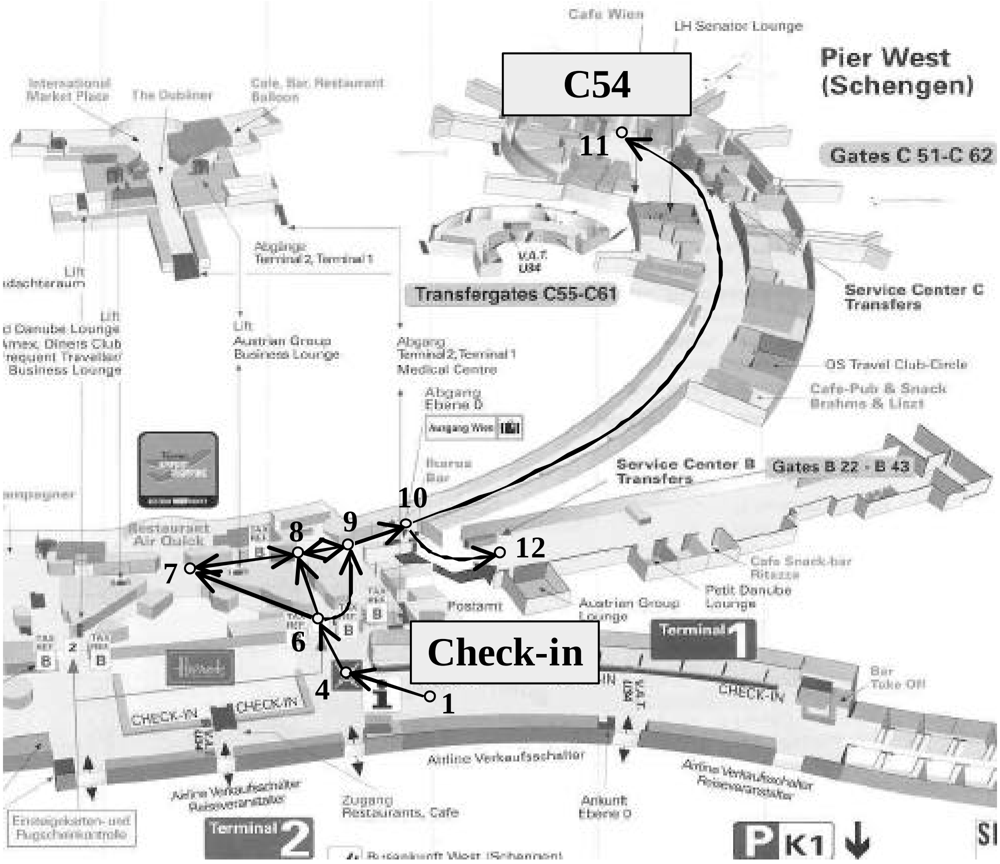

Figure 8: Finding one’s way from check-in to gate C54 at Vienna International Airport.

5.2 The test data

The wayfinding environment for this task is modeled through nine nodes. Table 1 shows all node states with their position, sign-information with the corresponding direction within the local reference frame of the node and the related “go-to” affordance, and the pairs where previous node positions of the agent are assigned incoming directions within the local reference frame of the node. One can allocate the orientation of the local reference frames to the nodes of the wayfinding environment in a random way. It makes sense though to adjust them in such a way that the number of axes pointing exactly to signs is a maximum. This facilitates the process of assigning directions to information. An example for allocating a local reference frame is shown in Figure 9 for the node with position 6, which is the decision point after passport control. The signs “A”, “A,C”, and “B,C” are localized at directions 1, 0, and 6 within the local reference frame of the node.

Position	Direction	Sign	Go-to	(Enter from, income dir)
1	1	A - D	4	(0,5)
4	7	A, B, C, D	6	(1,4)
6	1	A	7	(4,4), (7,1), (8,0), (9,6)
	0	A, C	8	
	6	B, C	9	
7	6	C	8	(6,5), (8,6)
8	2	A	7	(6,4), (7,2), (9,6)
	6	B, C	9	
9	2	A	8	(6,4), (8,2), (10,6)
	6	B, C	10	
10	6	C50 – C59	11	(9,2), (11,6)
	4	B	12	
11	7	C54 (at the gate)		(10,4)
12	6	B		(10,2)

Table 1: Node states for the test environment.

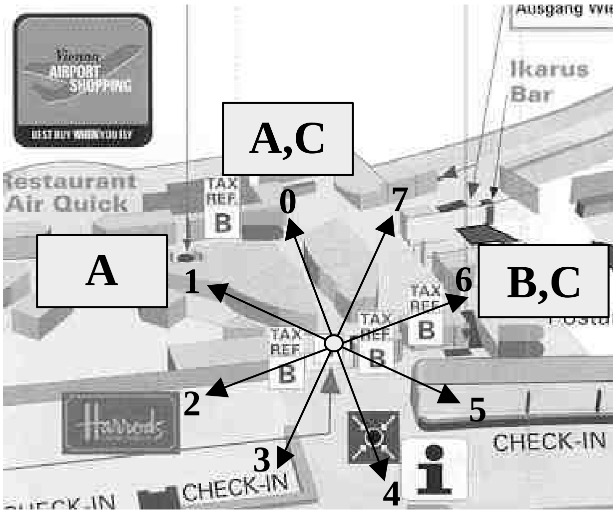

Figure 9: Local reference frame for node 6.

The formal representation of the wayfinding environment is of type `NodeStates` and called `vie`.

```
vie :: NodeStates

vie = [node1,node4,node6,node7,node8,node9,node10,node11,node12]

node1,node4,node6,node7,node8,node9,node10,node11,node12 :: NodeState

node1 = NodeState 1 [SpatialSit (Info 1 (GateSign2 (GateSignRange
  (LetterOnly 'A') (LetterOnly 'D')))) (1,4)] [(0,5)]

node4 = NodeState 4 [SpatialSit (Info 7 (GateSign1 (GateSignList
  [(LetterOnly 'A'),(LetterOnly 'B'),(LetterOnly 'C'),
  (LetterOnly 'D')]))) (4,6)] [(1,4)]

…
```

```
node9 = NodeState 9 [SpatialSit (Info 2 (GateSign (GateSignSingle
  (LetterOnly 'A')))) (9,8), SpatialSit (Info 6 (GateSign1
  (GateSignList [(LetterOnly 'B'),(LetterOnly 'C')]))) (9,10)]
  [(6,4),(8,2),(10,6)]
…
```

The cognizing agent is specified at the start of its wayfinding task. The agent has the identifier 1, starts at time instance 1 and position 1. Its goal is to find gate C54. The preferred directions of the agent are represented through the data type `Preferences` and called `pref`. The numbers (0-7) stand for the directions within the agent's egocentric reference frame. The ranking for preferred directions is given as numbers from 1 (highest preference) to 8 (lowest preference). The agent's state at the start is empty because the perceptual process has not yet started. We specify 5 as the incoming direction within the local reference frame of node 1. The agent has not yet decided on a "go-to" affordance, therefore we assign `unit0` to the `Decision` type. The history is empty at the beginning of the wayfinding task.

```
agent1 :: Agent
agent1 = Agent 1 1 1 (Gate 'C' 54) pref [] 5 unit0 []
pref :: Preferences
pref = [(0,1),(1,2),(2,4),(3,6),(4,8),(5,7),(6,5),(7,3)]
```

5.3 Analysis and results

We can now start the simulation by applying the analysis function `historyOfAgent` to the test environment (`vie`) and the agent at the start of its wayfinding task (`agent1`).

```
TestData> historyOfAgent vie agent1
Program execution error: REACHED GOAL
[History 1 20 11 (Gate 'C' 54)
  [(0,1),(1,2),(2,4),(3,6),(4,8),(5,7),(6,5),(7,3)] [SpatialSit (Info
  7 (GateSign (GateSignSingle2 (AtGate 'C' 54)))) (100,100)] 4 (0,0),
 History 1 19 11 (Gate 'C' 54)
  [(0,1),(1,2),(2,4),(3,6),(4,8),(5,7),(6,5),(7,3)] [] 2 (0,0),
 History 1 18 10 (Gate 'C' 54)
  [(0,1),(1,2),(2,4),(3,6),(4,8),(5,7),(6,5),(7,3)] [SpatialSit (Info
  6 (GateSign2 (GateSignRange1 (Gate 'C' 50) (Gate 'C' 59)))) (10,11),
  SpatialSit (Info 4(GateSign (GateSignSingle (LetterOnly 'B'))))
  (10,12)] 2 (10,11),
…]
```

The result shows that the execution of the function is stopped at time instance 20 because the agent has reached its goal. The complete history of the agent gives information about all perceptions, decisions, and actions of the agent during the performance of the wayfinding task.

To see how the simulation works when the agent is caught in a loop, the data about the test environment has to be slightly changed. We replace the specification of node 9 with the following one (Table 2).

Position	Direction	Sign	Go-to	(Enter from, income dir)
9	0	C	6	(6,3), (8,1), (10,5)

Table 2: New node state at node 9.

```
node9 = NodeState 9 [SpatialSit (Info 0 (GateSign (GateSignSingle
  (LetterOnly 'C')))) (9,6)] [(6,3),(8,1),(10,5)]
```

Now the test environment contains a loop because the sign at node 9 directs the agent back to node 6. The result of the `historyOfAgent` function is therefore an infinite list (which we cut after 30 steps due to the small number of nodes in the test environment).

```
[Agent 1 28 8 (Gate 'C' 54)
  [(0,1),(1,2),(2,4),(3,6),(4,8),(5,7),(6,5),(7,3)] [] 6 (0,0)
  [History 1 28 8 (Gate 'C' 54)
      [(0,1),(1,2),(2,4),(3,6),(4,8),(5,7),(6,5),(7,3)] [] 6 (0,0),
   History 1 27 6 (Gate 'C' 54)
      [(0,1),(1,2),(2,4),(3,6),(4,8),(5,7),(6,5),(7,3)] [SpatialSit
      (Info 1 (GateSign (GateSignSingle (LetterOnly 'A')))) (6,7),
      SpatialSit (Info 0 (GateSign1 (GateSignList [LetterOnly
      'A',LetterOnly 'C']))) (6,8), SpatialSit (Info 6 (GateSign1
      (GateSignList [LetterOnly 'B',LetterOnly 'C']))) (6,9)] 6 (6,8),
  …]]
```

We can now determine all consecutive positions the agent has reached during its task performance (`positionsOfAgent`) and find the loop the agent has been caught in (`findCycle`).

```
TestData1> positionsOfAgent vie agent1
[1,4,6,8,9,6,8,9,6,8,9,6,…,8,9,6,8,9,6,8,9,6,8] :: [Position]
TestData1> findCycle vie agent1
[6,8,9,6] :: [Position]
```

The result shows that the agent could not reach its goal because it was caught in a loop (nodes 6, 8, 9, and 6). This was caused by the fact that the agent was misinformed at node 9 (from where it was directed back to node 6). One can now check the history of the agent and will find that the reason for this misinformation is a sign (“C”) pointing in the wrong direction. To avoid such wayfinding difficulty the sign’s direction needs to be changed.

6. CONCLUSIONS AND FUTURE WORK

6.1 Results and conclusions

In this work we developed an agent-based process model to simulate people’s wayfinding behavior in unfamiliar buildings. The model concentrates on people’s information needs and does not focus on learning a spatial environment. It is different from previous computational models for wayfinding, which were built to investigate how mental representations are created, stored, and used. We call it a model for *perceptual wayfinding*.

The wayfinding model is grounded in people's experiences and consists of two tiers: simulated states of the environment and simulated beliefs of the agent. Individual components of the model were designed to have minimal functionality for achieving the set goal—the agent's ability to find a gate in the airport based on knowledge in the world. The components of the cognizing agent are its observation schema defining the framework and context of the agent's observations, its state representing the agent's beliefs about the environment, a wayfinding strategy to decide between two or more possible ways to the goal, and commonsense knowledge allowing the agent to locomote and understand the meaning of signs. The wayfinding environment is modeled as a graph, where nodes simulate decision points and edges simulate lines of movement.

When performing a wayfinding task, the agent starts with a goal description at a start node. During the navigation process it accumulates beliefs about the environment by observing task-relevant affordances and information at decision points. Affordances are possibilities for action with reference to the agent. Information is necessary for the agent to decide upon which affordances to utilize. The utilization of a so-called "go-to" affordance leads the agent from one node to another where it is provided with new percepts. A successful navigation corresponds to the agent's traversal from a start to a goal node.

The conceptual model is formalized as an algebra within a functional programming environment. We formally describe the interaction between agent and environment, and therefore fix the meaning of the conceptual model. The resulting specifications are executable, which allows formal checking of their syntax and prototyping to validate their semantics. Prototyping is done by applying the formal model to the case study: An agent has to find a specific gate at Vienna International Airport. The outcome demonstrates that the specifications for the agent-based wayfinding simulation developed in this work allow us to analyze the wayfinding process of a cognizing agent in an unfamiliar building. It is possible to determine if the agent is able to reach its goal based on external information, and if not, where and why wayfinding problems occur and what needs to be done to avoid them.

The model developed in this work is generic enough to be implemented and used for a variety of application domains where people need to find their ways in an unfamiliar environment. Designers can use it to simulate people's perceptions, decisions, and actions during the wayfinding process, to see if people can find their goals, and to discover wayfinding difficulties and their causes at decision points.

6.2 Directions for future work

We made various simplifying assumptions for the design of the agent-based model. Only those concepts and processes necessary to answer our research question were taken into consideration. The model could be extended by explicitly integrating all elements of the ontology and other physical and social-institutional affordances from the epistemology. This would allow simulating possible subtasks during finding one's gate in an airport, such as checking in at the check-in counter or buying goods at a duty-free store.

People's knowledge of the empirical world results from their perception of parts of the world. This knowledge is usually incomplete and imprecise. The two-tiered structure of our agent-based simulation allows for the integration of wayfinding errors such as encoding errors due to poor perceptual recording or recognition errors (Golledge 1999). Considering these errors and integrating a filter mechanism that selects the most relevant affordances and information for a given task would improve the model to simulate human behavior more closely.

It is not clear how people visually and semantically connect affordances and information. How does one know that a piece of information is related to one affordance rather than another? In our model information-affordance pairs are related as spatial situations based on human subject testing but the agent cannot do this automatically.

We specified one agent that is able to find a goal in a specific environment. In the real world, people also have the possibility to communicate with other people, e.g., ask somebody when they get lost. Simulation of social interaction between agents requires including multiple agents and communication operations within a multi-agent system. Communication of multiple agents is still a difficult problem due to the lack of domain-specific ontologies (Nwana and Ndumu 1999).

To assess the results of the formal model applied to the case study, one needs to compare them with results of human subject testing in the real environment. Such comparison will also help to test various parameters of the model, such as the proposed wayfinding strategy for the agent, and find additional ones to be included. Empirical data can be used to refine the model components so that the simulation results match real-world processes more closely.

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