ONTOLOGY AND EPISTEMOLOGY FOR AGENT-BASED WAYFINDING SIMULATION

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Abstract

Agent-based systems are used to simulate the behavior of people in various spatial environments. Designers of such systems need to give attention to ontological and epistemological concerns during the early stages of development to assure that the agent-based system is built upon a sound foundation. Only then is it possible to model the agent's behavior in a cognitively plausible way. This paper describes an ecological approach to model ontology and epistemology for agent-based wayfinding simulation. The ontology of the wayfinding environment is based on a subdivision into medium, substances, and surfaces. The epistemological model uses the concept of affordances, which we divide into physical, social-institutional, and mental affordances. Ontology and epistemology are both grounded in people's descriptions of their wayfinding experiences. A case study of wayfinding in airports demonstrates the applicability of the method.

1. INTRODUCTION

Geographical Information Science deals with the formal modeling of spatial processes and the interaction of humans with their environment in space and time (Frank 2000). Agent-based systems are tools to simulate such processes: autonomous agents perceive and act in an environment. They are therefore ideal candidates to imitate people's behavior during spatial courses of action, such as navigation or population movement, and its effects on the environment. All of them are areas of high interest in geographical research.

Ontology and epistemology of space are basic concerns during the development of an agent-based system. By defining the ontology of a specific domain, one describes what is in this domain in a general way. More specifically, from an information systems and artificial intelligence perspective, ontologies are content theories, because they identify specific classes of objects and relations that exist in some domain (Chandrasekaran *et al.* 1999, Frank forthcoming). Paying attention to epistemology allows the designer to focus on the agent's knowledge and beliefs. Both ontology and epistemology are necessary foundations for the set-up and functioning of an agent-based system, especially for modeling the agent's processes of perception, cognition, and action in a useful way.

This paper shows an approach to model ontology and epistemology for an agent-based wayfinding system. Wayfinding and orientation are important parts of people's daily lives (Golledge 1999). But many times people face problems because environments lack sufficient wayfinding information or their architectures are badly designed. Agent-based simulation of human wayfinding in a built environment helps to determine where people face wayfinding difficulties, why they face them, and how wayfinding information and design have to be altered to avoid these difficulties.

We look at ontology and epistemology from the viewpoint of ecological science (Shaw and Bransford 1977). Its main undertaking is to study the connections and reciprocity between

living systems and their environments. In particular, we consider the sub field of ecological psychology, which focuses on the information transactions between living systems and their environments. The world itself is seen as the information source for perception, which then determines the planning and execution of actions. Our main interest lies in designing and modeling a pragmatically useful ontology and epistemology of people's wayfinding behavior in airports. This is done based on interviews and the results serve as the foundation for a formal agent-based simulation tool with which we test airports for ease of wayfinding.

In section 2 we introduce agents and the ecological approach to psychology. Section 3 presents the ontological model of the wayfinding environment. The epistemological model, describing what the wayfinding agent can know about the environment, is discussed in section 4. Both frameworks are based on ecological concepts. Section 5 demonstrates the agent-based wayfinding system, which is built upon the shown ontological and epistemological foundations. In section 6 we present conclusions and suggest directions for future work.

2. RELATED WORK

The work presented here is based on agent theory and ecological science. In the following we briefly introduce the concepts used later.

2.1 Agents

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).

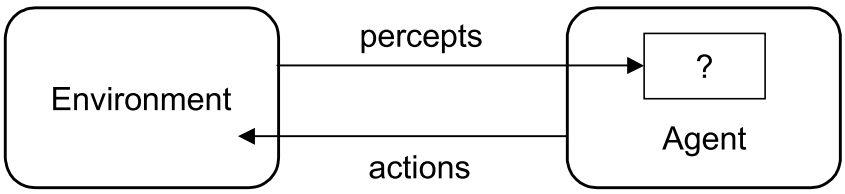

Figure 1: Agents interact with their environment (based on Russell and Norvig (1995)).

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. These abstract models can be implemented in different ways, depending on how the decision making of the agent is realized (Bryson 2000). The structure of the wayfinding agent used in this work is similar to that of a goal-based agent (Russell and Norvig 1995): State descriptions and goal information are combined with information about results of possible actions and then an action to achieve the goal is chosen.

2.2 Ecological viewpoint

The ecological approach to psychology was developed to solve the major problem of cognitive psychology, i.e., the problem of knowledge. It is based on ecological science, a multidisciplinary advance to the study of living systems, their environments, and the reciprocity between the two. Ecological psychology proposes to study the information transactions between living systems and their environments, especially in 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. The ecological approach is strongly opposed to the information-processing framework that is founded on a man-machine analogy. 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. He 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 (which is the result of illumination) and detected as units. Ambient light has structure and therefore information. This is at the heart of ecological optics, which is concerned with available information for perception. Gibson further argues that it is easier to perceive invariant units than to perceive all the variables separately.

In the following sections, Gibson's division of the environment is used as the ontological basis for modeling the wayfinding environment, and affordances serve as structures describing what the agent can know about it.

3. ONTOLOGICAL CONCERNS – THE WAYFINDING ENVIRONMENT

Ontologists have been criticized for not putting enough effort into describing an ontological theory of people's everyday objective environments (Smith forthcoming). With the help of a case study, i.e., wayfinding in airports (Figure 2), we show how both ontology and epistemology (focusing on the wayfinding agent) of such a *behavioral environment* (Smith forthcoming) can be modeled based on ecological concepts. Following Gibson (1979), we subdivide the wayfinding environment into medium, substances, and surfaces.

Figure 2: Airport environment.

3.1 The medium

People move in a *medium*, which is for light, sound, and odor coming from different sources in the environment. In such a medium there are points of observation and lines of locomotion. During wayfinding in an airport, passengers move along lines of locomotion and occupy different points of observation to gather information about the environment. The absolute reference axis within the medium is defined by gravity, namely up-down.

3.2 The substances

The *substances* differ in chemical and physical composition, and are structured in a hierarchy of inter-nested units. In order to arrive at the ontology, we extracted substances (i.e., nouns) from interviews, in which people described their experiences during wayfinding in airports (Raubal *et al.* 1997). Synonyms were then merged and categories of substances formed. This method is based on "ontologies from texts" (Kuhn 2000).

Figure 3 gives a taxonomic tree of substances in an airport. It is based on "is-a" relations, which allows making transitive inferences. We can infer from "a traveler is a cognizing agent" and "a cognizing agent is a substance" that "a traveler is a substance." One has to distinguish here between intensional definitions, i.e., category names chosen by the

constructor of the ontology, and extensional definitions, i.e., names used by interviewees to refer to specific instances of categories. We differentiate between two main categories of substances, which can be divided further: *cognizing agents* and *non-cognizing objects*. This is similar to Wordnet's division of the top- level category "thing" into the subcategories "living" and "nonliving" (Miller 1990). Cognizing agents in an airport can be travelers or airport staff (with instances ticketing agent, check-in agent, etc.). We further divide non-cognizing objects into *bona-fide* and *fiat objects*, depending on whether the boundaries of the objects exist independently of or are created by human cognitive acts (Smith 1995). Sub-categories of bona-fide objects in airports are architectural component, information device (e.g., sign, monitor), counter (e.g., check-in, passport control), or gate. Sub-categories of fiat objects are area (e.g., waiting area, gate area) and navigational element (e.g., path, decision point).

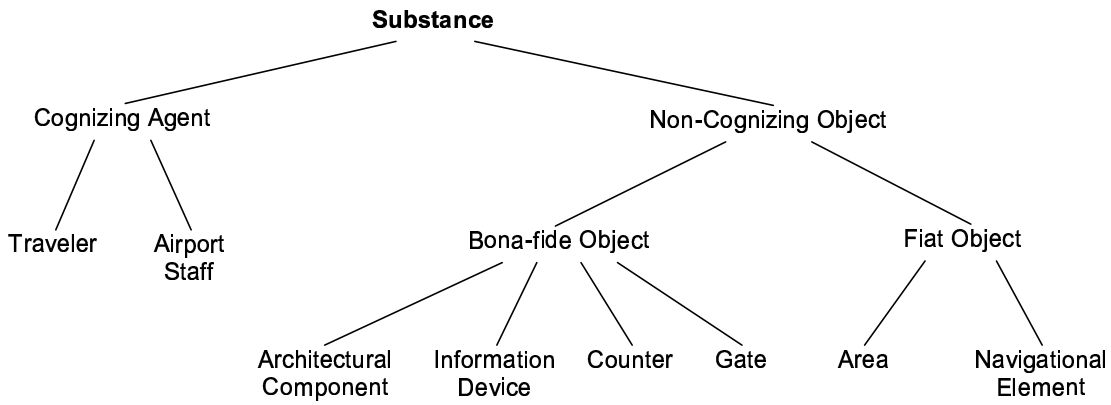

Figure 3: Intensional category definitions in a taxonomic tree of substances in an airport.

In addition to this taxonomy, the ontology also comprises partonomies, which are hierarchies based on "part-of" relations (Tversky 1990). Figure 4 shows examples of the partonomy for *terminal*, which is an *architectural component*. All elements of this partonomy have physical boundaries and serve as receptacles for people's projections of fiat boundaries.

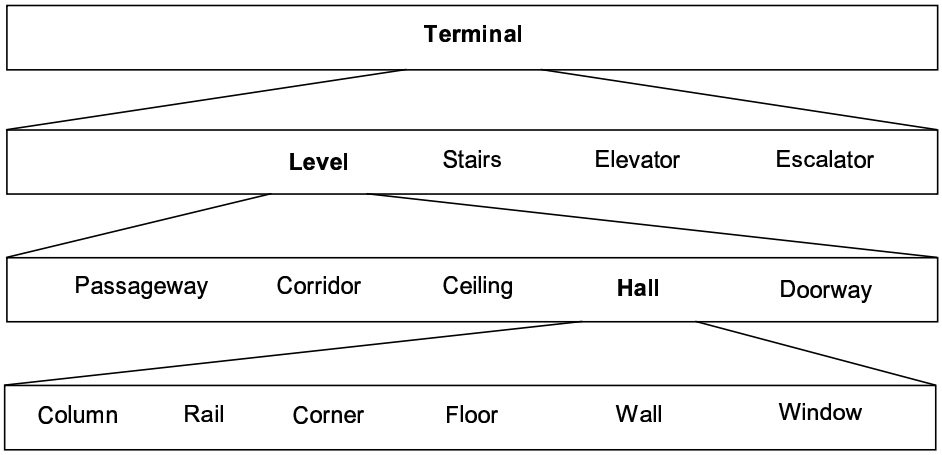

Figure 4: Partonomy for *terminal* in an airport.

3.3 The surfaces

The medium is separated from the substances of the environment by *surfaces*. Gibson argues that the layout of surfaces has an intrinsic meaning for behavior. This will be dealt with in section 4.

4. EPISTEMOLOGICAL CONCERNS – THE AGENT

The epistemological question of what the wayfinding agent can know about the environment and how it can accumulate such knowledge is modeled through affordances. According to Gibson, the composition and layout of surfaces constitute what they afford. Affordances are specific combinations of the properties of substances and surfaces taken with reference to an observer. This is the reason why we promote a distinction between ontological and epistemological concerns: what the agent can know about the environment depends on the agent's properties and the task. Consider the scenario of the case study: A mother is going on a flight with her 3-year-old son. In order to go from the departure hall to the gate, she first has to check in at the check-in counter. Based on the task and the mother's properties (e.g., being an adult), the check-in counter affords for her to put her tickets on the counter so that the check-in agent can give her boarding passes. Although her 3-year-old son perceives the same

object, namely the check-in counter, his perceived affordances are different, because of his properties (e.g., being too short to put something on the counter) and his task (e.g., to follow his mother).

Table 1 shows affordances perceived by an adult traveler during the task of finding her way in an airport. These (i.e., verbs) were also extracted from the interviews and synonyms merged.

Substance	*Affordances*
Traveler	approach, follow, avoid, disappear, talk to, ask, provide information, behave, confirm
Check-in agent	look for, approach, talk to, ask, provide information, check in, show ticket to, behave
Stairs	go up/down, stand, wait, pay attention
Doorway	look through, enter, go through, put through
Area	look for/around, move around/through, access, leave, stand, wait, enclose, include, expect, spend time
Column	go around/towards, obstruct, block, divide
Sign	look for, go towards, stand out, recognize, check, catch one's eye, read, provide information, find one's way, advertise, follow, direct
Monitor	look for, go towards, reflect, display, search, check, read, provide information, confirm
Check-in counter	look for, go to, stand in front, line up, check in, put ticket, get boarding pass
Passport control	look for, go to/through, enter, block, line up, show passport, show boarding pass
Path	move along, branch, curve, begin/end, remember, select, direct
Decision point	look around, pass, turn, wait, decide, search, select, orient

Table 1: Affordances from substances for an adult traveler while finding her way to the gate.

Affordances belong to different realms: physical, social-institutional, and mental. *Physical affordances* require bundles of physical substance properties that match the agent's capabilities and properties. The "climbability" affordance of stairs depends on the ratio of

riser height / leg length (Warren 1995), doorways afford going through if the agent fits through the opening, and monitors afford reflecting light depending on lighting conditions, surface properties, and the agent's viewpoint.

Many times it is not sufficient to derive affordances from physical properties only because people act in environments and contexts with social and institutional rules (Smith 1999). The utilization of perceived affordances, although physically possible, is often socially unacceptable or even illegal. The physical properties of passport control afford moving through. In the context of going to one's gate in an airport, passport control affords for the traveler to show her passport and boarding pass, and only then to move through. In terms of Barker this constitutes a physical-behavioral unit (Barker 1968), including both physical constraints and social forces. Furthermore, the whole realm of social interaction between agents is based on *social affordances*: Another traveler affords talking to, asking, and behaving in a certain way.

Physical and social-institutional affordances are the sources of *mental affordances*. In order to utilize a mental affordance, the agent needs to perform an internal operation, such as "decide." A monitor affords displaying letters and numbers, (e.g., flight departures) and reflecting light, but it also affords the traveler searching for her gate (i.e., performing the internal operation of matching her goal information). A path affords remembering and selecting, a decision point affords orienting and deciding, etc.

5. AGENT-BASED WAYFINDING SIMULATION

We use the ecological approach for the design of an agent-based tool to simulate people's wayfinding processes in buildings. The coupling of the cognizing agent and the environment, in which it perceives and acts, is based on the ontological and epistemological foundations described in sections 3 and 4. The wayfinding model (Figure 5) integrates the agent's cognitive schema and perceptual structures within a Sense-Plan-Act (SPA) approach (Gat

1998). It focuses on external knowledge to explain actions of the agent performing wayfinding tasks. The environment provides percepts (i.e., affordances from cognizing agents and non-cognizing objects) to the agent; the agent decides upon and performs actions in the environment, which in turn provides new percepts; and so on. Information (such as from signs) is necessary for the agent to decide upon which affordances to utilize. An internal cognitive schema (Neisser 1976) guides the agent's processes of perception, decision, and action during the wayfinding task. This schema includes information about the task and goal, and a minimum of wayfinding strategies and commonsense knowledge necessary to perform the task. The task description directs visual perception in such a way that the agent samples only task-relevant information and affordances. The wayfinding 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).

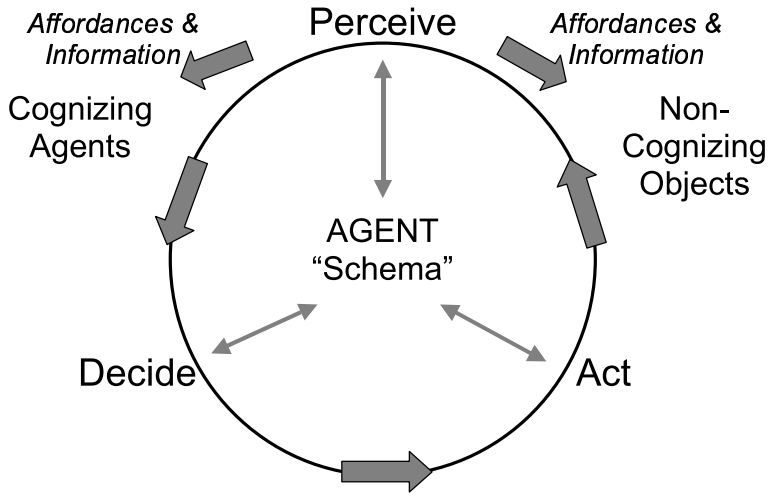

Figure 5: Process model for wayfinding.

For formalization we selected an algebraic approach and defined classes with operations. The formal model is represented in the functional language Haskell[1] (Thompson 1999) and it is therefore possible to check its consistency and simulate test cases such as finding the way

[1] The code can be downloaded from ftp://ftp.geoinfo.tuwien.ac.at/raubal/wayfindSimulCode.ZIP.

from the check-in counter to gate C54 at Vienna International Airport (Raubal and Worboys 1999).

6. CONCLUSIONS AND FUTURE WORK

Research in spatial ontology and epistemology is an important basis for the setup of an agent-based model for wayfinding. Perception and cognition of the agent can only be modeled in a useful way if the ontological and epistemological foundations are well established. In this work we try to connect ontology of space, epistemology of space, and spatial cognition, in order to come up with a practical agent-based simulation tool for wayfinding in an airport. Such a tool should help to design airports that facilitate wayfinding.

The ontological and epistemological work presented here is based on interviews from human subjects concerning wayfinding in airports. More testing, such as performed by Mark *et al.* (1999), needs to be done in order to see if proper categories were formed and to test different instances for category membership. Future research will have to focus on different behavioral environments - ontological and epistemological theories have to be developed and integrated in order to extend the agent-based simulation tool. Further work might focus on the relation between affordances and information, the influence of attributes such as color on the perception of affordances, and the comparison between wayfinding by agents and wayfinding by people in the real world.

7. REFERENCES

R. Barker (1968) Ecological Psychology - Concepts and Methods for Studying the Environment of Human Behavior. Stanford University Press, Stanford.

J. Bryson (2000) Cross-Paradigm Analysis of Autonomous Agent Architecture. Journal of Experimental and Theoretical Artificial Intelligence 12(2): 165-190.

B. Chandrasekaran, J. Josephson, and R. Benjamins (1999) What Are Ontologies, and Why Do We Need Them? IEEE Intelligent Systems (1): 20-26.

A. Frank (2000) Geographic Information Science: New methods and technology. Journal of Geographical Systems 2(1): 99-105.

A. Frank (forthcoming) Ontology for Spatio-Temporal Databases. in: T. Sellis et al. (Eds.), Spatiotemporal Databases: The Chorochronos Approach. Springer.

E. Gat (1998) On Three-Layer Architectures. in: D. Kortenkamp, P. Bonnasso, and R. Murphy (Eds.), Artificial Intelligence and Mobile Robots. AAAI Press.

J. Gibson (1979) The Ecological Approach to Visual Perception. Houghton Mifflin Company, Boston.

R. Golledge, Ed. (1999) Wayfinding Behavior - Cognitive Mapping and Other Spatial Processes. Johns Hopkins University Press, Baltimore.

W. Kuhn (2000) Ontologies from Texts. in: A. Caschetta (Ed.), GIScience 2000, Savannah, Georgia, USA, pp. 49-51.

D. Mark, B. Smith, and B. Tversky (1999) Ontology and Geographic Objects: An Empirical Study of Cognitive Categorization. in: C. Freksa and D. Mark (Eds.), Spatial Information Theory - Cognitive and Computational Foundations of Geographic Information Science, International Conference COSIT '99, Stade, Germany, pp. 283-298.

G. Miller (1990) Wordnet: An Online Lexical Database. Int. Journal of Lexicography 3(4): 235-312.

U. Neisser (1976) Cognition and Reality - Principles and Implications of Cognitive Psychology. Freeman, New York.

D. Norman (1988) The Design of Everyday Things. Doubleday, New York.

M. Raubal, M. Egenhofer, D. Pfoser, and N. Tryfona (1997) Structuring Space with Image Schemata: Wayfinding in Airports as a Case Study. in: S. Hirtle and A. Frank (Eds.), Spatial Information Theory—A Theoretical Basis for GIS, International Conference COSIT '97, Laurel Highlands, PA. Lecture Notes in Computer Science 1329, pp. 85-102, Springer, Berlin.

M. Raubal and M. Worboys (1999) A Formal Model of the Process of Wayfinding in Built Environments. in: C. Freksa and D. Mark (Eds.), Spatial Information Theory - Cognitive and Computational Foundations of Geographic Information Science, International Conference COSIT '99, Stade, Germany, pp. 381-399.

S. Russell and P. Norvig (1995) Artificial Intelligence - A Modern Approach. Prentice-Hall International, London.

R. Shaw and J. Bransford, Eds. (1977) Perceiving, Acting, and Knowing - Toward an Ecological Psychology. Lawrence Erlbaum Ass., Hillsdale, New Jersey.

B. Smith (1995) On Drawing Lines on a Map. in: A. U. Frank and W. Kuhn (Eds.), Spatial Information Theory-A Theoretical Basis for GIS. Lecture Notes in Computer Science 988, pp. 475-484, Springer, Berlin-Heidelberg-New York.

B. Smith (1999) Les objets sociaux. Philosophiques 26(2): 315-347.

B. Smith (forthcoming) Objects and Their Environments: From Aristotle to Ecological Ontology. in: A. Frank (Ed.), The Life and Motion of Socioeconomic Units. Taylor & Francis, London.

S. Thompson (1999) Haskell - The Craft of Functional Programming. Addison-Wesley, Harlow, England.

B. Tversky (1990) Where partonomies and taxonomies meet. in: S. Tsohatzidis (Ed.), Meanings and prototypes: Studies on Linguistic Categorization. pp. 334-344, Routledge, London.

W. Warren (1995) Constructing an Econiche. in: J. Flack, P. Hancock, J. Caird, and K. Vicente (Eds.), Global Perspectives on the Ecology of Human-Machine Systems. 1, pp. 121-156, Lawrence Erlbaum Associates, Hillsdale, New Jersey.

M. Wooldridge (1999) Intelligent Agents. in: G. Weiss (Ed.), Multiagent Systems - A Modern Approach to Distributed Artificial Intelligence. pp. 27-77, MIT Press, Cambridge, MA.