Mappings For Cognitive Semantic Interoperability

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SUMMARY

Semantic interoperability for geographic information and services has been a main research area within Geographic Information Science. Success in solving semantic interoperability problems has been limited though, because many efforts are based on so-called realist semantics approaches. Considering the fact that geographic information is eventually used by people, it is necessary to account for people's (geographic) concepts and their semantic relation to different system views of the same concepts. In this paper we propose to tackle the problem of Cognitive Semantic Interoperability for geographic information by defining mappings between conceptual spaces. Such spaces can be utilized to formally represent the meanings of concepts within geometrical structures, both from a system's and a user's perspective. We present a formal definition of possible mappings—projections and transformations—and the occurring losses of information. A wayfinding service scenario is used to demonstrate the applicability and usefulness of the approach.

KEYWORDS: *Cognitive Semantic Interoperability, conceptual spaces, mappings.*

INTRODUCTION

Achieving semantic interoperability for geographic information has been a major research goal of the GIScience community. It is defined as the capacity of (geographic) information systems and services to work together without the need for human intervention (Harvey *et al.* 1999). Semantic heterogeneity arises when two contexts lead to different interpretation of the information (Wache, Vögele et al. 2001). Nevertheless, these systems and services eventually support human users in their decision-making and therefore people's understanding of terms must be accounted for (Miller forthcoming). Current approaches to solve the semantic interoperability problem are based on realist semantics, which defines meaning independent of a human user. In order to account for human concepts a cognitive semantics approach is needed. In this paper we make a case for Cognitive Semantic Interoperability.

The foundation of this work is Gärdenfors' notion of *conceptual spaces*, i.e., sets of quality dimensions within a geometrical structure (Gärdenfors 2000). Such spaces can be formally defined as vector spaces, which allow for the representation of concepts and instances of these concepts. Vector spaces have a metric, therefore they permit the calculation of semantic distances between the instances, i.e., between points in the space, and between instances of concepts and their prototypes (Rosch 1978). Furthermore, one can assign weights to the quality dimensions to account for the fact that people's concepts are highly context-dependent (Raubal 2004). Semantic interoperability can essentially be defined as translations between the meanings of concepts. In order to tackle this problem from a cognitive semantics perspective, we define two classes of mappings—projections and transformations—including the occurring losses of information. Such formal definition of mappings between conceptual spaces can eventually be used to close the gap between psychological user variables on the one hand and physical system variables on the other hand (Norman 1986).

COGNITIVE SEMANTIC INTEROPERABILITY FOR GEOGRAPHIC INFORMATION

When trying to achieve semantic interoperability for geographic information, two major questions arise (Kuhn 1996):

- How can one ensure that the meaning intended by the designer of a geographic information service is communicated to the user?
- How can the meaning implied by geographic data and concepts be communicated from suppliers to consumers?

Geographic information systems and geospatial information services need to communicate concepts and information to their users in a cognitively adequate way. This ensures that information can be understood by different users and in different contexts, and interpreted in the way the information providers intended. Such matching of understandings and intended meanings requires theories of how humans conceptualize their environment and how they express their concepts in languages.

Semantic interoperability problems can be tackled in two ways: from a realist semantics perspective or from a cognitive semantics perspective. Here, we argue for *Cognitive Semantic Interoperability*, which is built on theories of cognitive semantics and human spatial cognition. Cognitive semantics claims that the meanings of terms are in people's heads. Meanings are therefore mappings to conceptual structures, which themselves refer to real-world entities. Cognitive semantics tries to give answers to many of the problems a realist semantics account of reality faces, such as explaining processes of learning and the construction of mental objects that do not correspond to real-world features (Gärdenfors 2000). The realist approach to semantics assumes that meaning consists only of relationships between abstract symbols and elements in real-world models. Therefore, correct reasoning is achieved by logical manipulation of such symbols and elements. This point of view lacks a place for people, because according to realist semantics the relation of symbols to the world stays the same, whether there are people in it or not (Lakoff 1987). But information systems, which can interact with their users in a comprehensible way, require different mental knowledge representations of different users (Knauff *et al.* 2002). As Rosch puts it: "It should be emphasized that we are talking about a perceived world and not a metaphysical world without a knower." (Rosch 1978, p.29)

SEMANTIC REFERENCE SYSTEMS AND CONCEPTUAL SPACES

In recent work, Kuhn (2003) argued that as a generalization to spatial and temporal reference systems, semantic reference systems are needed to ground the meaning of terms and translate it between different information communities. A semantic reference system comprises ontologies specifying conceptualizations and methods for mappings between them. Such a system must be embedded in a formalism that supports the computation of these mappings (Kuhn and Raubal 2003; Raubal and Kuhn 2004). We propose here a formal cognitive semantics approach to represent conceptualizations and to translate between different conceptualizations.

It utilizes Gärdenfors' idea of conceptual spaces—sets of quality dimensions with a geometrical or topological structure for one or more domains (Gärdenfors 2000). Such spaces can be utilized for knowledge representation and sharing. They support the paradigm that concepts are dynamical systems (Barsalou 2003), i.e., their structure and the importance of each dimension can change over time and for different contexts. A domain is represented through a set of integral dimensions, which are distinguishable from all other dimensions. For example, the color domain may be represented by its quality dimensions hue, saturation, and brightness. Concepts and their prototypes are modeled as n-dimensional regions and every object is represented as a point in a conceptual space. This allows for expressing the similarity between two objects as the distance between their points in the conceptual space.

In (Raubal 2004), a methodology to formalize conceptual spaces as vector spaces was introduced. There, it is also demonstrated how to measure semantic distances between instances of a concept in these spaces and how to define a simple mapping between spaces. Here, we explore further the formal definition of possible mappings between conceptual vector spaces, i.e., *what kinds of mappings can occur in an application, how can these mappings be calculated, and what is the loss of information*. A case study from the geospatial domain—wayfinding services with landmarks—is used to demonstrate the usefulness and applicability of these mappings. This formal framework serves as a foundation for the theory of semantic reference systems, which takes into account people's conceptualizations and therefore supports Cognitive Semantic Interoperability.

MAPPING CONCEPTUAL VECTOR SPACES

The major hypothesis of this work is that translating the meaning of concepts between different users and information communities can be achieved through mappings between conceptual spaces. Formally, a conceptual vector space is defined as $\mathbf{C}^n = \{(c_1, c_2, \ldots, c_n) \mid c_i \in \mathbf{C}\}$ where the c_i are the quality dimensions. A quality dimension can also represent a whole domain and in this case $c_j = \mathbf{D}^n = \{(d_1, d_2, \ldots, d_n) \mid d_k \in \mathbf{D}\}$. Mappings between conceptual vector spaces can either be projections or transformations.

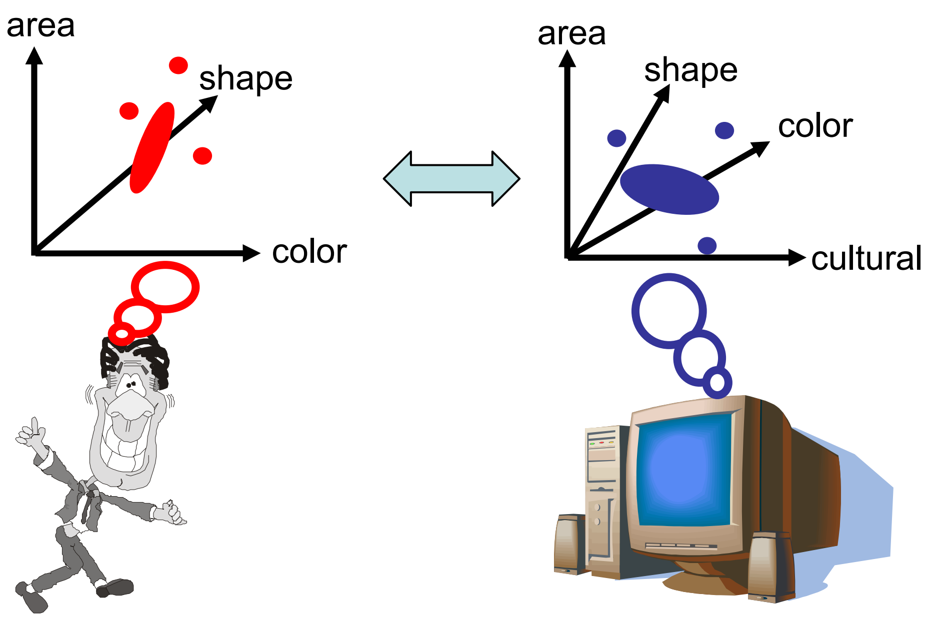

Figure 1: Conceptual space for façade with prototypical regions and instances from user and system perspectives.

Projections reduce the complexity of the space by reducing its number of dimensions. We define a partial mapping (R_{proj}: $C^m \rightarrow C^n$) where $n < m$ and $C^m \cap C^n = C^n$. Thereby, the semantics of the mapped quality dimensions must not change or can be mapped by rules. For example, consider a wayfinding service, which communicates route instructions with landmarks to its users (Raubal and Winter 2002; Nothegger *et al.* 2004). The system automatically extracts façades of buildings to serve as landmarks in the instructions and thereby follows the system designer's concept of façade, which is most likely different from the user's conceptualization of a façade. Lets assume the system's conceptual space for façade consists of the quality dimensions façade area, shape, color, and cultural importance, and the user's space comprises the dimensions façade area, shape, and color (Figure 1).

Then a projection from system to user space leads to a reduction from 4 to 3 quality dimensions. The loss of information L (in terms of quality dimensions) can be defined as $L = C^m \setminus C^n$. This leads to L = {cultural importance}.

Transformations involve a major change of quality dimensions, e.g., the addition of new dimensions (whose semantics might be expressed in terms of the old ones). Here, the partial mapping is defined as (R_{trafo}: $C^m \rightarrow C^n$) where

- ($n < m$ and $C^m \cap C^n \neq C^n$)
- or ($n = m$ and $C^m \cap C^n \neq C^n$)
- or ($n > m$).

The loss of information depends mainly on how much semantics of elements of C^m, which are not part of C^n, can be mapped. We therefore define a factor E that represents the parts of $C^m \setminus C^n$, which are captured by $C^n \setminus C^m$. Then for the first two cases, the loss of information is either

- $L = C^m \setminus C^n - E$ or
- $L = C^m \setminus C^n$ (if $C^m \setminus C^n$ cannot be expressed through dimensions of C^n).

In the case of ($n > m$) one needs to distinguish between $C^m \cap C^n = C^m$ where $L = 0$ and $C^m \cap C^n \neq C^m$ where L is calculated as before.

This is illustrated by the following case: Let the system space for façade consist of the dimensions façade area, shape, color (RGB—Red, Green, Blue—scale), and cultural importance. Let the user space consist of the dimensions façade area, shape, color (based on perception, HSB—Hue, Saturation, Brightness—scale), and visibility (i.e., the prominence of a façade). The dimensions façade area and shape can be directly mapped; the different color scales can be mapped by applying an algorithm using color conversion formulas (see, for example, http://www.easyrgb.com/math.html), therefore E = {$color_{RGB}$}. This leads to L = {$color_{RGB}$, cultural importance} – {$color_{RGB}$} = {cultural importance}, i.e., information regarding the cultural importance of a building is lost during this transformation process. When going in the reverse direction, i.e., transforming the user space into the system space, the information loss amounts to L = {visibility}. In practice, this means that visibility, which is an important quality dimension with respect to people's concept of façade in the context of landmarks for wayfinding instructions, is not accounted for in the automatic extraction process of the system.

The proposed framework can also be used for a quantitative comparison of mappings between different representations. This addresses questions such as which conceptual representation is semantically closer to a given one or fits a specific purpose better. In that case, the scales of the quality dimensions need to be standardized and weighted to account for the dimensions' importance in different contexts.

CONCLUSIONS AND FUTURE WORK

This paper makes a case for Cognitive Semantic Interoperability. We defined a formal framework for mappings between conceptual spaces that allows for translating the meanings of concepts between information systems and people. In addition, it is possible to quantify the loss of information, which inevitably occurs for most mappings. Examples were given for concepts occurring in a wayfinding service. This framework is based on cognitive semantics by representing the meanings of concepts as mappings to conceptual structures (spaces). In this way it also serves as a foundation for the implementation of semantic reference systems that support Cognitive Semantic Interoperability.

Future work needs to apply the framework to other case studies and compare the results to human subject tests about communication of concepts and possible misunderstandings. In the ideal case the vectors representing quality dimensions form a basis of the conceptual vector space. In practice this is hard to achieve because for various domains not all dimensions are totally independent. For example, in the color domain, saturation and brightness influence each other. It will be necessary to investigate dependencies between quality dimensions for a concept and their influences on the calculations. Furthermore, it is crucial to examine whether partial mappings are sufficient to capture all possible cases of translation. For example, cases where quality dimensions of a concept are split into two or more dimensions cannot be represented through functions.

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