Cognitive modeling with conceptual spaces

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Abstract. This paper presents a formal approach to cognitive modeling by utilizing conceptual spaces. Conceptual spaces were introduced by Peter Gärdenfors as geometric and topologic representations that mediate between the symbolic and subconceptual cognitive levels. They can be used for knowledge representation and to explain cognitive reasoning. The goal here is to discuss both the advantages of this approach, and limitations regarding its potential as a 'universal' form of cognitive representation that also serves as a representational model for human spatial reasoning.

Keywords: Conceptual spaces, concepts, representation, cognitive reasoning.

1 Introduction

The work presented here tackles two main topics of the workshop, i.e., *formal approaches to cognitive modeling* and *human-machine interaction in geospatial information systems*. Communication between systems and their users is made possible through the mutual understanding of terms and concepts. If we want geospatial services and tools to give better answers to user questions it is necessary to bridge and eventually resolve the discrepancy between user concepts and system concepts. Concepts can be formally represented in *conceptual vector spaces*—sets of quality dimensions within geometrical structures (Gärdenfors, 2000; Raubal, 2004). These spaces allow for representing instances and types of concepts, measuring semantic distances between them, and modeling different contexts by assigning weights to their dimensions. Furthermore, one can semantically compare the system and user spaces by applying projections and transformations (Raubal, 2005). This way it is possible for the system to adapt the semantics of its concepts to the user's semantics, which eventually leads to improved human-computer interaction.

From a cognitive modeling perspective, formal conceptual spaces offer a possible *mental model* as a representation of the *mental world*, which is a representation of the real world and concerned with the inner workings and processes within the brain and nervous system (Palmer, 1978). This results in various questions concerning the cognitive plausibility and adequacy of conceptual space representations, their possible limitations with regard to explaining mental (spatial) information processing, and their potential to be integrated with other cognitive models.

2 Formal conceptual spaces

The notion of *conceptual space* was introduced as a framework for representing information at the conceptual level (Gärdenfors, 2000). Conceptual spaces can be utilized for knowledge representation and sharing, and support the paradigm that concepts are dynamical systems (Barsalou, 2003). Sowa (2006) argued that conceptual spaces are a promising geometrical model for representing abstract concepts as well as physical images.

A conceptual space is a set of quality dimensions with a geometrical or topological structure for one or more domains. Domains are represented through sets of integral dimensions, which are distinguishable from all other dimensions. For example, the color domain is formed through the dimensions hue, saturation, and brightness. Concepts cover multiple domains and are modeled as n-dimensional regions. Every object or member of the corresponding category is represented as a point in the conceptual space. This allows for expressing the similarity between two objects as the spatial distance between their points. Recent work has focused on representing actions and functional properties in conceptual spaces (Gärdenfors, 2007).

In (Raubal, 2004), a methodology to formalize conceptual spaces as vector spaces was presented. 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 $c_j = \mathbf{D}^n = \{(d_1, d_2, \ldots, d_n) \mid d_k \in \mathbf{D}\}$. Vector spaces have a metric and therefore allow for the calculation of distances between points in the space. This can also be utilized for measuring distances between concepts, either based on their approximation by 'prototypical points' or 'prototypical regions' (Schwering & Raubal, 2005a). The calculation of these *semantic distances* requires that all quality dimensions of the space are represented in the same relative unit of measurement. Assuming a normal distribution, this is ensured by calculating the z-scores for the individual values (Devore & Peck, 2001). For specifying different contexts one can assign weights to the quality dimensions of a conceptual vector space. This is essential for the representation of concepts as dynamical systems, because the salience of dimensions may change over time. $\mathbf{C}^n$ is then defined as $\{(w_1c_1, w_2c_2, \ldots, w_nc_n) \mid c_i \in \mathbf{C}, w_j \in \mathbf{W}\}$ where $\mathbf{W}$ is the set of real numbers.

3 Representing cognitive processes with conceptual spaces

It has been argued that due to their modeled quality dimensions, conceptual spaces can be utilized to represent one of the major aspects of semantics and reasoning, i.e., similarity (Gärdenfors, 2004; Goldstone & Son, 2005). Indeed, it is hard to imagine situations in our daily lives that do not in some way include reasoning that involves similarity, e.g., when searching for particular entities, grouping entities into categories, or to be more concrete, simply trying to change a light bulb (Barsalou, 1983). Furthermore, conceptual spaces account for prototype effects by allowing for the representation of prototypes as n-dimensional regions in the space. This is based on Rosch's structural theory of centrality, where prototypical members had been found to correspond to the means of attributes that have a metric (Rosch, 1978).

Instead of approximating prototypes and concepts by points (i.e., vectors) in the space, it is possible to represent them by regions, which allows for integrating shape and size within the similarity measure (Schwering & Raubal, 2005a). This also accounts for the fact that people's similarity judgments are asymmetric (A. Tversky, 1977).

Conceptual spaces are inherently spatial in that they are modeled by a geometrical or topological structure. In order to be used as an adequate model for spatial reasoning though, it is necessary to explicitly represent spatial relations, in particular topologic and metric relations. When determining semantic similarity between geospatial concepts, spatial relations play a major role in the calculation process. All geospatial objects have a position in space with regard to some spatial reference system and consequently a spatial relation to each other. Spatial relations are therefore also central characteristics on the conceptual level (Donnelly & Bittner, 2005). Schwering & Raubal (2005b) presented an approach of integrating spatial relations into semantic similarity measurements between different geospatial concepts represented in conceptual spaces. It was demonstrated that such integration improves the quality of the measurements by enhancing the accuracy of their results. On the downside, representing spatial relations as quality dimensions in the conceptual space is a tedious process because each dimension does not only need to represent one concept and its values, but one concept and its values with regard to a second concept (when modeled as binary relations). Figure 1 shows an example from the domain of hydrology by representing a 'nearness' relation. In this research, the simplifying assumption was made that quality dimensions of a conceptual space are independent. This is often not true and it is therefore necessary to investigate the covariances between dimensions, and to account for these in the conceptual space representations.

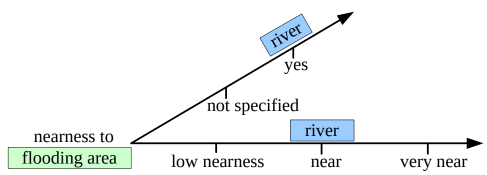

Figure 1: Modeling relations as dimensions on Boolean and ordinal scale (from (Schwering & Raubal, 2005b).

Conceptual spaces as cognitive models can also be used to explain processes of learning and forgetting, which correspond to the addition and subtraction of quality dimensions, and changes within the internal structure and scale of particular dimensions.

3 Open research questions

Although conceptual spaces have proven to be promising candidates for cognitive models in terms of representing concepts and instances, and serving as an explanatory framework for cognitive processes, several open questions remain:

1. What is the potential of conceptual spaces for serving as a ‘universal’ form of cognitive representation? Using geometric models is only one possible way of representing information at the conceptual level. Different views on the nature of conceptual representations in the human cognitive system exist, such as mental imagery (Kosslyn, 1994) or schematic perceptual images extracted from modes of experience (Barsalou et al., 1993). Could such images be represented in or combined with conceptual spaces? Would such combination be similar to a cognitive collage (B. Tversky, 1993)? What are the components of a hybrid cognitive model—similar to the argument for unified theories (instead of theory) of cognition made by (Newell, 1990)—that covers ‘the whole ground’? Human participants tests may help assess the validity of geometrical representations of concepts and point to limitations of conceptual spaces as a representational model.
2. When formally specifying conceptual spaces, the simplifying assumption is often made that the quality dimensions of the conceptual spaces are independent. As previously stated, this is not always true. It will be necessary to investigate the covariances between dimensions and to account for these in the representations of the conceptual spaces. Again, human participants tests are a way to identify the quality dimensions for a concept and to infer their dependencies, which would lead to nonorthogonal axes in the representation.
3. Several researchers have argued against a geometric approach for concept representation and similarity measurement for the reasons that the axioms of minimality, symmetry, and triangle inequality do not hold cognitively. With conceptual vector spaces it seems possible to account for these phenomena by assigning different weights depending on the context. In this way, dissimilarity of the same concept depending on the viewpoint and asymmetric semantic distances could be represented. The axiom of triangle inequality seems to be violated only when different contexts are mixed (e.g., geographical and political), such as in the example given by (A. Tversky, 1977). It seems though that accounting for context needs more than assigning weights. For example, context rules (Keßler, Raubal, & Janowicz, 2007) may be applied to conceptual spaces that allow for both addition and removal of dimensions, but also for a re-segmentation of dimensions.
4. In order to evaluate the potential of conceptual spaces as an approach to modeling mental spatial information processing for human spatial reasoning, more tests and simulations with geographic use cases are required—see (Barkowsky, 2002) for an example within the domain of visual imagery. Such simulations will further demonstrate the advantages and limitations of conceptual spaces as a representational model for human spatial reasoning.

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