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Logical lateration – A cognitive systems experiment towards a new approach to the grounding problem

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Abstract

Human beings are able to extract linear ordering information, such as preferences, rankings, priorities, temporal ordering, and other numerical or quasi-numerical representations as well as estimations of spatial positions in mental maps or mental images from purely qualitative statements. From the perspectives of both cognitive science and logics, it is an interesting question how such *imagery* can arise from logical structures as provided by language. This article presents a cognitive system, for brevity called *imaginer*, which is built around a non-monotonic reasoning mechanism, called *logical lateration*. The system numerically evaluates model sets of knowledge bases. We show results from an experiment showing that the model sets by themselves, i.e., without any ontology, give rise to context-dependent coordinate representations of a knowledge base, which the system can draw. Being both a logic-based as well as an analogous cognitive system, the experiment provides a fresh perspective on the grounding problem.
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1. Introduction

The human cognitive system is able to extract ordering information, such as estimates of spatial positions or preference rankings, from qualitative statements. This plays an important role in many tasks where human intelligence currently surpasses machine intelligence. Given qualitative knowledge about the location of an object, such as, "north of A, to the south-west of B," human beings are easily able to form a *mental image* or *mental map* about where an object or event is located (Taylor & Tversky, 1992). A number of experiments (Kosslyn, 1980; Kosslyn, 1994) suggest that such mental representations are actually analogous. Participants seem to work with a mental image and use operations such as panning and zooming to inspect this image when asked to answer a query about the depicted objects. The discovery of place-cells in the brains of rats that fire when the animals recognize a place (O'Keefe, 1976) provides further support for this hypothesis. More recent neuroimaging results suggest a more complex relationship: Knauff, Kassubek, Mulack, and Greenlee (2000, 2002) showed that only areas responsible for higher visual functions are involved but not the visual cortex itself, a result suggesting that imagery happens directly at the interface between logic and perception.

The experiments do not yet explain, however, how human participants can mentally or physically *draw* such maps or images, when given purely qualitative textual information about unknown locations or objects. Moreover, not only the visuo-spatial but also other domains, such as time, preference or rank, are conceptualized as linear or hierarchical orderings. Experimental results suggest that the mental representations used in reasoning involve

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a mixture of dimensional and hierarchical information (Tversky & Sattath, 1979), and we seem to be able to switch between hierarchical, i.e. organized as a tree-structure, and dimensional, i.e. organized in a quasi-numerical representation, models (Tversky, 1977). Remarkably, however, these models are not fixed, as one would expect if they are similar to images, but subjects make different decisions based on context (Tversky & Gati, 1978), and seem to be able to effortlessly switch between viewpoints, indicating again that the representation format is at the interface between logic and perception.

While there are many logical formats, theories, and mechanisms, both logical and numerical, which can be used to express, and reason about, ordered dimensions, such as time, space, or utility, there is currently no theory showing that there is a direct connection between logical representations and ordered dimensions. Without such a connection, we need an extra system, cognitive mechanism, or special ontology that can translate between perception and logic. In a nutshell, this paper presents such a direct connection between logic and perception.

Taddeo and Floridi (2005) argue that any complete solution of the grounding problem has to work without any assumptions of a base ontology, a condition termed the *Zero Semantic Ontology Condition*. With the considerable advances made on the grounding problem by research such as that of Steels (2008) studying the pathway from perception to logic, it may be a small but certainly relevant piece of the puzzle to be able to also show the path from logic to perception.

2. Material and methods

From a logical point of view, the continuous domains of perception,[1] such as space, time, or measurement values, can be modeled easily on the basis of thresholds (Galton, 2000), and are relevant for a number of applications, including robotics (Schmidtke & Woo, 2007) and pervasive computing (Schmidtke, Hong, & Woo, 2008). Integration with general purpose reasoning languages is often difficult (Wessel, 2001; Haarslev, Lutz, & Möller, 1999). A logical language specifically targeting continuous domains is the contextual logic language called *Context Logic* (Schmidtke et al., 2008). Originally designed to give a semantics (Schmidtke & Woo, 2009) for verifying early context-aware computing systems (Hupfeld & Beigl, 2000; Dey & Abowd, 2000; Jiang & Steenkiste, 2002; Jang & Woo, 2003), the context logic family today comprises languages (Schmidtke, 2016; Schmidtke et al., 2008; Schmidtke & Beigl, 2011) for reasoning about continuous domains on several complexity layers within the expressiveness-tractability spectrum (Levesque & Brachman, 1987) and the evolutionary cognitive hierarchy (Gärdenfors, 2005; Schmidtke & Woo, 2008). The main distinction of context logic is its aim for ontological minimalism, which makes it particularly easy to map to other logics. It is also designed, like hybrid logics (Blackburn, 2000), to be close to linguistic uses of context. The logic has only one syntactic type, for simplicity called *context*, in contrast to First Order Logic which has variables, predicates of different arity, and functions of different arity.[2]

The language used in this article is inferentially slightly stronger than the lightweight fragment of (Schmidtke & Beigl, 2011) and sufficiently simple to be expressed in propositional logic. This makes it easy to transfer results to related approaches based on propositional logic. The proposed format on which the reasoning mechanism works is a bit vector format similar to that of symbolic-connectionist approaches (Kanerva, 1988; Hummel & Holyoak, 2003), but with a different focus: the operations in focus are logical rather than associative. Association, a core component of human memory retrieval, has received considerable attention in cognitive science. And we know that even relations can be learned in a connectionist manner (Regier, 1996). It would be desirable, however, to be able to connect the associative format on a fundamental level to logic in order to better understand how higher cognitive functions mechanisms, and abilities can be rooted in such a format. The paper thus contributes to finding a connection between the associative bit vector substrate and higher levels of cognition leveraging logic.

Given the above results from cognitive science research suggesting that a cognitively adequate system for human-like reasoning should be *non-monotonic* and *analogous* as well as *logical* and *qualitative*, the hypothesis to verify in this research is that *logical lateration*, a non-monotonic framework that works by counting model sets has all four properties. The key idea of logical lateration is to process information into a superposition of possible worlds and to determine how many of these worlds match a given description. The paper demonstrates how a logic knowledge-base can automatically give rise to a numerical interpretation that can be drawn.

The logical lateration system itself belongs to the category of non-monotonic reasoning systems. As in other non-monotonic reasoning systems, such as circumscription (McCarthy, 1980), default logic (Reiter, 1980), belief revision (Gärdenfors, 2003), abduction (Hobbs, Stickel,

[1] When talking about *representations of continuous domains of perception* in this article, this refers to not necessarily continuous representations of presumably continuous physical dimensions. We do not need to assume that the cognitive systems itself can handle continuity in a mathematical sense, e.g., understand $\sqrt{2}$. Axioms ensuring continuity in a mathematical sense require a formalism equivalent to second order predicate logic, and from a cognitive point of view we would not want a lower-level representation system to require such a representationally powerful logic. That is, while reality may be continuous, the representation format we employ here corresponds to the mathematical notion of *density*: we can always add a point between two different points.

[2] Ontologically, context logic can be associated with a four-dimensionalist, mereological view, although we would assume a higher-dimensional feature space as the underlying domain. Cf. Quine, Churchland, and Føllesdal (2013) for a philosophical discussion.

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