A meta-theory for knowledge representation

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Abstract. An unsolved problem in AI is a representation of meaningful interpretation. In this paper we suggest that a process model of cognitive activity can be derived from a Peircean theory of categories. By virtue of the fundamental nature of categories, the obtained model may function as a meta-theory for knowledge representation.

1 Introduction

An unsolved problem in AI is a representation of meaningful interpretation. The complex nature of this problem is illustrated by Searle's famous Chinese room argument thought experiment (CRA) [6]. Throughout the CRA debate Searle maintained that meaningful (semantic) and computational (syntactic) interpretation must be qualitatively different.

From the perspective of knowledge representation (KR) we may identify two extreme positions in the reaction by computer science on the above problem of AI. According to the first one, meaningful are those concepts that have that property by definition. Traditional theories of KR, in a broad sense, including program specification and theorem proving, facilitate this conception. In our view, the underlying reasoning may not be correct. Although individual concepts obtained by human activity can be meaningful, a combination of such concepts may not possess that property. This is a consequence of the inadequacy of the used ontology for a definition of genuine meaningfulness (we will return to this point in the next section) and the possibility of a combination of concepts of arbitrary length in KR (in the lack of a definition we may not be able to derive if a combination of concepts is meaningful). According to the second position above, meaningful concepts arise through interpretation (hence meaningful interpretation is a tautology). Following this conception, a representation of (meaningful) interpretation is in need of a paradigmatically new ontology, enabling meaningful and not-meaningful to be represented qualitatively differently.

In this paper we elaborate on the second position above, and how this view can be supported computationally. To this end we consider the question what is involved in meaningful interpretation. For, even if we may not be able to capture the real nature of interpretation, knowledge about its properties may allow us to build computer programs approximating and thereby enhancing human processing, e.g., through simulating the operations involved in it.

Below we begin with an analysis of traditional KR. We return to an overview of a novel ontology and knowledge representation, in Sect. 3.

2 Traditional knowledge representation

As meaningful interpretation is our common experience, its properties must be respected by models of genuine human processing. In this section we suggest that traditional KR may not be able to comply with this requirement and that, some of the problems in computer science could be a consequence of the above deficiency of traditional modeling as well. A property shared by traditional theories of KR is their foundation in the Aristotelian categorical framework. Aristotle's ten categories can be distinguished in two qualitatively different types: unique *substances*, that are independent; and accidental categories or *attributes*, such as quantity, quality and relation, that are 'carried' by a substance. Clearly, in the Aristotelian framework, actual and meaningful attributes (hence also such substance–attribute relations) cannot be represented in a qualitatively different fashion. From this we conclude that his ontology may not be satisfactory for the definition of a model of authentic interpretation.

Notably the same problem, the lack of a suitable ontology, seems to have been the driving force behind important discoveries in knowledge modeling, in the past. An example is the problem of program specification, revealed by E.W. Dijkstra, in 1968. By virtue of the possibility of an unbridled use of 'goto' statements, enabled by programming languages at that time, programs were frequently error-prone. Dijkstra suggested a systematic use of types of program constructs, which he called Structured Programming. Briefly, this states that three ways of combining programs –sequencing, selection, and iteration (or recursion)– are sufficient to express any computable function. Another example is the problem of an apparent diversity of models of natural language syntax, exposed by A.N. Chomsky, in 1970. In his X-bar theory, Chomsky claimed that among their phrasal categories, all human languages share certain structural similarities, that are lexical category, relation, and phrase.

In our view, the trichotomic character of classification, illustrated by the examples above, may not be accidental. We foster the idea that a representation of meaningful concepts, and in general, the definition of a model of meaningful interpretation asks for a three-categorical ontology. A theory satisfying the above condition can be found in the categorical framework by C.S. Peirce (1839-1914). By virtue of the fundamental nature of categories, and the relation between Peirce's categories and his signs, Peircean theory is considered by many to be a theory of the knowable hence a meta-theory for knowledge representation.

3 Towards a new ontology

According to Peirce [3], phenomena can be classified in three categories, that he called firstness, secondness, and thirdness. Firstness category phenomena involve a monadic relation, such as the relation of a quality to itself. Secondness category phenomena involve a dyadic relation, such as an actual (or ad-hoc) relation between qualities. Thirdness category phenomena involve a triadic relation, such as an interpretation of a relation, rendering an explanation or a reason to it, thereby generating a meaningful new concept. The three Peircean categories are irreducible, for example, triadic relations cannot be decomposed into secondness category actual relations. From a KR perspective, the categories can be considered to be qualitatively different. For instance, secondness is qualitatively less meaningful than thirdness. Conform its relational character, triadic classification can be applied recursively. Below, a category can be designated by its ordinal number, e.g., secondness by the integer '2'.

Our examples, in Sect. 2, exhibit the aspects of Peirce's three categories. A sequence, a lexical item, are independent phenomena, exhibiting the aspect of firstness (1). A selection between alternatives, that are involved, a language relation, defined by constituent language symbols, e.g., in a syntactic modification structure, are relation phenomena, exhibiting the aspects of secondness (2). An iteration, abstracting alternatives and sequences of instructions into a single instruction, a phrase, merging constituent expressions into a single symbol, are closure phenomena, exhibiting the aspects of thirdness (3).

Peirce's three categories are related to each other according to a relation of dependency: categories of a higher ordinal number involve a lower order category. A distinguishing property of the Peircean categorical schema is that only thirdness can be experienced, firstness may only appear through secondness, and secondness only through thirdness. This subservience relation of the three categories implies that categories of a lower ordinal number evolve to hence need a higher order category.

The sample classifications, in Sect. 2, satisfy the conditions of dependency between the categories. For instance, an iteration (3) may involve alternatives (2), and in turn, a sequence of instructions (1). The other way around, a sequence of instructions (1) may only appear as an iteration (3) through the mediation of alternatives (2). Note that an alternative may consist in a single choice, and an iteration a single cycle, degenerately.

A knowledge representation respecting the properties of meaningful interpretation must be able to comply with both types of dependency above and, conform the recursive nature of the Peircean categorical scheme, it must have the potential to be applied recursively. These conditions may put a great burden on a computational implementation of a Peircean knowledge representation.

Having introduced the basic properties of the three categories, we are ready to offer an informational analysis to the dependencies between them.

3.1 Informational analysis

In past research we have shown that, from Peirce's theory of categories, a knowledge representation can be derived [5]. This goal can be achieved in two ways: the first is, by offering an aspectual analysis to signs and assigning a process interpretation to the obtained hierarchy of sign aspects (see Fig. 1); the second is, through an informational analysis of phenomena. In [4] we have shown that the representations obtained by the two derivations can be isomorphic. By virtue of its more straightforward presentation, in this paper we will elaborate on the second alternative above.

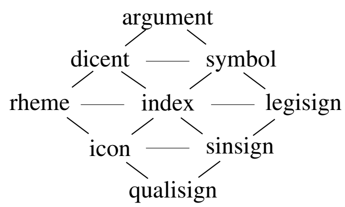

Fig. 1: A process interpretation of Peirce's hierarchy of sign aspects, introduced in [5]. Horizontal lines are used to designate interaction events between representations of the input from different perspectives (cf. sign aspects). The input of the process is associated with the qualisign position

Because thirdness can only be experienced (i.e. interpreted), perceived phenomena must be a thirdness. Following a theory of cognition [2], perceived phenomena must be an event representation of a change involved in the input interaction. Put differently, only if there is a change, an interaction may appear as an event. By virtue of the dependency between the three categories, perceived phenomena (cf. thirdness) involve a relation (cf. secondness), and in turn, a quality (cf. firstness). Below, in our analysis of phenomena we restrict ourselves to interactions between a pair of qualities, that we designate by q_2 and q_1. The term quality may refer to a single quality and a collection of qualities, ambiguously.

Qualities involved in an interaction must be independent, otherwise their co-occurrence may not involve a change hence an event. An interaction may be interpreted however, as a phenomenon of any category, potentially. From these conditions we may draw the conclusion that qualities involved in an interaction must convey information about their possible interpretation as a phenomenon of any one of the three categories.

In this paper we suggest that information involved in an interaction can be represented by a hierarchy of pairs of categorical information of qualities. See Fig. 2(a). An example is the pair (3,2), designating information enabling a meaningful (3) and a relational interpretation (2), involved in q_2 and q_1, respectively. In the domain of language processing, the type of information represented by (3,2) may correspond to information involved in the syntactic subject of a sentence, standing for an actually existent entity (cf. thirdness) and implicating (cf. secondness) the appearance of a characteristic property, represented by the predicate.

Following our informational analysis, in the next section we recapitulate a result from [5], and show how on the basis of a theory of cognitive activity a process can be derived which is isomorphic and analogous to the Peircean categorical representation depicted in Fig. 2(a). It is by virtue of *this* relation that the suggested process model can be called a Peircean model of KR.

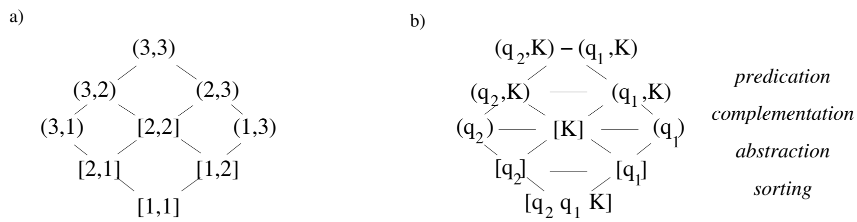

Fig. 2: (a) A hierarchical representation of information involved in an interaction between a pair of qualities, q_2 and q_1. A pair of integers is used to designate categorical information involved in q_2 and q_1 (in this order). (b) The process model of cognitive activity. Horizontal lines are used to designate interaction events between different input representations. The types of interpretation used are displayed on the right-hand side in italics

4 Process model

Following [2], we assume that the goal of cognitive activity is the generation of a response on the input stimulus. In a single interaction, the stimulus, appearing as an effect, is affecting the observer, occurring in some state. The qualities of this state (q_2) and effect (q_1), as well as memory knowledge (K) triggered by q_2 and q_1, form the input for information processing ($[\mathsf{q}_2\ \mathsf{q}_1\ \mathsf{K}]$). See Fig. 2(b). The occurring state (q_2) and effect qualities (q_1) are in the focus of the observer; the activated memory knowledge (K) is complementary.

From an informational stance, the goal of human processing is to establish a relation answering the question: why this effect is occurring to this state. In order to achieve this goal, the observer or interpreting system has to sort out the two types of qualities and context occurring in the input interaction ($[\mathsf{q}_2]$, $[\mathsf{q}_1]$, $[\mathsf{K}]$), abstract the type of qualities that are in focus into independent collections ((q_2), (q_1)), complete those collections with complementary knowledge by the interpreting system ($(\mathsf{q}_2,\mathsf{K})$, $(\mathsf{q}_1,\mathsf{K})$), and through predication, merge the obtained representations into a single relation ($(\mathsf{q}_2,\mathsf{K})$–$(\mathsf{q}_1,\mathsf{K})$).

The isomorphism between the diagrams in Fig. 2 must be clear. An analogy between positions in the two diagrams can be explained as follows. The input, $[\mathsf{q}_2\ \mathsf{q}_1\ \mathsf{K}]$, expressing a potential for interpretation, corresponds to information represented by $[1{,}1]$ (note that secondness and thirdness category information may be involved in $[1{,}1]$, but that information is as yet not operational). The expressions obtained by sorting, $[\mathsf{q}_2]$, $[\mathsf{q}_1]$, and $[\mathsf{K}]$, exhibiting a potential for a relation involved in the input interaction, correspond to information represented by $[2{,}1]$, $[1{,}2]$ and $[2{,}2]$. For instance, $[2{,}1]$ is an expression of relational information involved in q_2, and a potential for interpretation (e.g., as a relation) involved in q_1. An explanation of a relation between other positions in the two diagrams can be given analogously.

4.1 Limitations and potential of the model

Due to its computational character (cf. secondness), the model in Fig. 2(a) may not be able to represent triadic relations hence also meaningful interpretation (cf. thirdness). We may ask: can this model offer more than traditional theories of knowledge representation can?

In our view the answer can be positive. Through respecting the types of distinctions that can be signified by phenomena (cf. the nine positions in Fig. 1), the proposed theory may enable a systematic development of models of human processing. Due to a lack of a suitable ontology, traditional KR may not have this potential.

By virtue of the fundamental nature of categories, the process model, depicted in Fig. 2(b), may *uniformly* characterize human processing in any domain hence can be used as a meta-theory (and methodology) for KR as well. An advantage of a uniform representation of knowledge is its potential for merging information in different domains into a single representation by means of *structural coordination*, which can be more efficient than merging via translations between different representations. Experimental evidence for a uniform representation of information by the brain can be found in cognitive research by [1]. In this paper the authors show, by means of fMRI measurements, that language-related ('syntactic') and world-related ('semantic') knowledge processing can be quasi-simultaneous in the brain. Their results imply that human processing may not have sufficient time for a translation between representations in different knowledge domains (at least, in the domains tested) hence the use of a uniform representation could be inevitably necessary.

Illustrations of the theoretical potential of the proposed model of KR in various domains, including natural language processing, reasoning and mathematical conceptualization, can be found in [5].

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