Prototypes Vs Exemplars in Concept Representation

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Abstract: Concept representation is still an open problem in the field of ontology engineering and, more in general, of knowledge representation. In particular, it still remains unsolved the problem of representing "non classical" concepts, i.e. concepts that cannot be defined in terms of necessary and sufficient conditions. In this paper we review empirical evidence from cognitive psychology, which suggests that concept representation is not an unitary phenomenon. In particular, it seems that human beings employ both prototype and exemplar based representations in order to represent non classical concepts. We suggest that a similar, hybrid prototype-exemplar based approach could be useful also in the field of formal ontology technology.

1 INTRODUCTION

This article deals with the problem of representing non classical concepts in formal ontologies. By non classical concepts we mean concepts that cannot be represented in terms of sets of necessary and/or sufficient conditions. After introducing the problem (sect. 2), we review some empirical evidence from cognitive psychology, which suggests that concept representation is not an unitary phenomenon (sect. 3). In particular, prototype and exemplar based models of non classical concepts are both plausible, and can account for different aspects of human abilities. In sect. 4 we argue that these results could suggest the adoption of a hybrid approach in the field of formal ontologies; in sect. 5 we sketch the proposal of an architecture for concept representation based on both prototypes and exemplars. Some concluding remarks follow (sect. 6).

2 REPRESENTING NON CLASSICAL CONCEPTS

The representation of common sense concepts is still an open problem in ontology engineering and, more in general, in Knowledge Representation (KR) (see e.g. Frixione and Lieto, in press). Cognitive Science showed the empirical inadequacy of the so-called "classical" theory of concepts, according to which concepts should be defined in terms of sets of necessary and sufficient conditions. Rather, Eleanor Rosch's experiments (Rosch, 1975) – historically preceded by the philosophical analyses by Ludwig Wittgenstein (Wittgenstein, 1953) – showed that ordinary concepts can be characterized in terms of prototypical information.

These results influenced the early researches in knowledge representation: the KR practitioners initially tried to keep into account the suggestions coming from cognitive psychology, and designed artificial systems – such as frames and early semantic networks – able to represent concepts in "non classical" (prototypical) terms (for early KR developments, see Brachman and Levesque, 1985).

However, these early systems lacked clear formal semantics and a satisfactory meta-theoretic account, and were later sacrificed in favour of a class of formalisms stemmed from the so-called structured inheritance semantic networks and the KL-ONE system (Brachman and Schmoltze, 1985). These formalisms are known today as *description logics* (DLs, Baader et al., 2010). DLs are logical formalisms, which can be studied by means of traditional, rigorous metatheoretic techniques developed by logicians. However, they do not allow exceptions to inheritance, and the possibility to represent concepts in prototypical terms. From this point of view, therefore, such formalisms can be seen as a revival of the classical theory of concepts.

As far as prototypical information is concerned, such formalisms offer only two possibilities: representing it resorting to tricks or ad hoc solutions, or, alternatively, ignoring it. For obvious reasons, the first solution in unsuitable: it could have disastrous consequences for the soundness of the knowledge base and for the performances of the entire system. The second choice severely reduces the expressive power of the representation. For example, in information retrieval terms, this could severely affect the system's recall. Let us suppose that you are interested in documents about flying animals. A document about birds is likely to interest you, because most birds are able to fly. However, flying is not a necessary condition to being a bird (there are many birds that are unable to fly). So, the fact that birds usually fly cannot be represented in a formalism that allows only the representation of concepts in classical terms, and the documents about birds will be ignored by your query.

Nowadays, DLs are widely adopted within many fields of application, in particular within the area of ontology representation. For example, OWL is a formalism in this tradition, which has been endorsed by the World Wide Web Consortium for the development of the Semantic Web. However, DL formalisms leave unsolved the problems of representing concepts in prototypical terms.

Within the field of logic oriented KR, rigorous approaches exist, designed to make it possible the representation of exceptions, and that therefore are, at least in principle, suitable for dealing with (some aspects of) “non-classical” concepts. Examples are fuzzy and non-monotonic logics. Therefore, the adoption of logic oriented semantics is not necessarily incompatible with the representation of prototypical effects. Various fuzzy and non-monotonic extensions of DL formalisms have been proposed. Nevertheless, such approaches pose various theoretical and practical problems, which in part remain unsolved (see Frixione and Lieto, 2010 for a discussion).

As a possible way out, we outline here a tentative proposal that goes in a different direction, and that is based on some suggestions coming from empirical cognitive science research. Within the field of cognitive psychology, different positions and theories on the nature of concepts are available; all of them are assumed to account for (some aspects of) prototypical effects in conceptualisation (see e.g. Murphy, 2002 and Machery, 2009). Here we shall take into account two of such approaches, namely prototypes and the so-called exemplar view.

According to the prototype view, knowledge about categories is stored in terms of prototypes, i.e. in terms of some representation of the “best” instances of the category. For example, the concept CAT should coincide with a representation of a prototypical cat. In the simpler versions of this approach, prototypes are represented as (possibly weighted) lists of features.

According to the exemplar view, a given category is mentally represented as set of specific exemplars explicitly stored within memory: the mental representation of the concept CAT is the set of the representations of (some of) the cats we encountered during our lifetime.

These approaches turned out to be not mutually exclusive. Rather, they seem to succeed in explaining different classes of cognitive phenomena, and many researchers hold that all of them are needed to explain psychological data (see again Murphy, 2002 and Machery, 2009). In this perspective, we propose to integrate some of them in computational representations of concepts.

Prototype and exemplar based approaches to concept representation are, as mentioned above, not mutually exclusive, and they succeed in explaining different phenomena. Exemplar based representations can be useful in many situations. According to various experiments, it can happen that instances of a concept that are rather dissimilar from the prototype, but are very close to a known exemplar, are categorized quickly and with high confidence. For example, a penguin is rather dissimilar from the prototype of BIRD. However, if we already know an exemplar of penguin, and if we know that it is an instance of BIRD, it is easier for us to classify a new penguin as a BIRD. This is particularly relevant for concepts (such as FURNITURE, or VEHICLE) whose members differ significantly from one another.

Exemplar based representations are easier and faster to acquire, when compared to prototypes. In some situations, it can happen that there is not enough time to extract a prototype from the available information. Moreover, the exemplar based approach makes the acquisition of concepts that are not linearly separable easier (see Medin and Schwanenflugel, 1981). In the following section we shall review some of the available empirical evidence concerning prototype and exemplar based approaches to concept representation in psychology.

3 EXEMPLARS VS. PROTOTYPES IN COGNITIVE PSYCHOLOGY

As anticipated in the previous section, according to the experimental evidence, exemplar models are in many cases more successful than prototypes. Consider the so-called “old-items advantage effect”. It consists in the fact that already known items are usually more easily categorized than new items that are equally typical (see Smith and Minda, 1998 for a review). For example: it is easier for me to classify my old pet Fido as a dog (even supposing that he is strongly atypical) than an unknown dog with the same degree of typicality. This effect is not predicted by prototype theories. Prototype approaches assume that people abstract a prototype from the stimuli presented during the learning phase, and categorize old as well as new stimuli by comparing them to it. What matters for categorization is the typicality degree of the items, not whether they are already known or not. By contrast, the old-item advantage is banal to explain in the terms of the exemplar paradigm.

This is correlated to a further kind of empirical evidence in favour of exemplar theories. It can happen that a less typical item can be categorized more quickly and more accurately than a more typical category member if it is similar to previously encountered exemplars of the category (Medin and Schaffer, 1978). Consider the penguin example mentioned in the previous section: a penguin is a rather atypical bird. However, let us suppose that some exemplar of penguin is already stored in my memory as an instance of the concept BIRD. In this case, it can happen that I classify new penguins as birds more quickly and more confidently than less atypical birds (such as, say, toucans or hummingbirds) that I never encountered before.

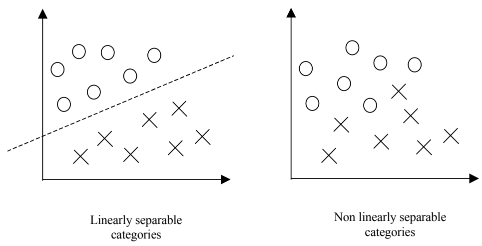

Figure 1: Linearly separable and non separable categories.

Another important source of evidence for the exemplar model stems from the study of linear separable categories (see, again, Medin and Schwanenflugel, 1981). Two categories are linearly separable if and only if it is possible to determine to which of them an item belongs by summing the evidence concerning each attribute of this item. For example, let us suppose that two categories are characterized by two attributes, or dimensions, corresponding to the axes in fig. 1. These categories are linearly separable if and only if the category membership of each item can be determined by summing its value along the x and y axes, or, in other terms, if a line can be drawn, which separates the members of the categories.

According to the prototype approach, people should find it more difficult to form a concept of a non-linearly separable category. Subjects should be faster at learning two categories that are linearly separable. However, Medin and Schwanenflugel (1981) experimentally proved that categories that are not linearly separable are not necessarily harder to learn. This is not a problem for exemplar based theories, which do not predict that subjects would be better at learning linearly separable categories. In the psychological literature, this result has been considered as a strong piece of evidence in favour of the exemplar models of concept learning.

The above mentioned results seem to favour exemplars against prototypes. However, other data do not confirm this conclusion. Moreover, it has been argued that many experiments favourable to the exemplar approach rest on a limited type of evidence, because in various experimental tasks a very similar category structure has been employed (Smith and Minda, 2000). Nowadays, it is commonly accepted that prototype and exemplars are not competing, mutually exclusive alternatives. In fact, these two hypotheses can collaborate in explaining different aspects of human conceptual abilities (see e.g. Murphy, 2002 and Machery, 2009).

An empirical research supporting the hypothesis of a multiple mental representation of categories is in Malt (1989). This study was aimed to establish if people categorize and learn categories using exemplars or prototypes. The empirical data, consisting in behavioral measures such as categorization probability and reaction time, suggest that subjects use different strategies to categorize. Some use exemplars, a few rely on prototypes, and others appeal to both exemplars and prototypes. A protocol analysis of subjects’ descriptions of the adopted categorization strategy confirms this interpretation (a protocol analysis consists in recording what the subjects of an experiment say after the experiment about the way in which they performed the assigned tasks). Malt (1989) writes:

"Three said they used only general features of the category in classifying the new exemplars. Nine said they used only similarity to old exemplars, and eight said that they used a mixture of category features and similarity to old exemplars. If reports accurately reflect the strategies used, then the data are composed of responses involving several different decision processes" (p. 546-547).

These findings are consistent with other well known studies, such as Smith et al. (1997) and Smith and Minda (1998). Smith et al. (1997) found that the performances of half of the subjects of their experiments best fitted the prototype hypothesis, while the performances of the other half were best explained by an exemplar model. Therefore, it is plausible that people can learn at least two different types of representation for concepts, and that they can follow at least two different strategies of categorization. Smith and Minda (1998) replicated these findings and, additionally, found that during the learning, subjects' performances are best fitted by different models according to the features of the category (e.g., its dimensions) and the phase of the learning process, suggesting that when learning to categorize artificial stimuli, subjects can switch from a strategy involving prototypes to a strategy involving exemplars. They also found that the learning path is influenced by the properties of the learned categories. For example, categories with few, dissimilar members favour the use of exemplar-based categorization strategies. Thus, psychological evidence suggests that, in different cases, we employ different categorization mechanisms.

Summing up, prototype and exemplar approaches present significant differences, and have different merits. We conclude this section with a brief summary of such differences. First of all, exemplar-based models assume that the same representations are involved in such different tasks as identification (e.g., "this is the Tower Bridge") and categorization (Nosofsky, 1986). This contrasts with prototype models, which assumes that these tasks involve different kinds of representations. Furthermore, prototype representations synthetically capture only some central, and cognitively relevant, aspects of a category, while models based on exemplars are more analytical, and represent *in toto* the available knowledge concerning the instances of a given category.

This is related to another aspect of divergence, which pertains the categorization process. Both prototype and exemplar models assume that the *similarity* between prototypical/exemplar representations and target representations is computed. The decision of whether the target belongs to some category depends on the result of this comparison. However, important differences exist. According to the prototype view, the computation of similarity is usually assumed to be *linear*. Indeed, since prototypes are synthetic representations, all information stored in them is relevant. Therefore, if some property is shared by the target and by some prototype, this is sufficient to increase the similarity between them, independently from the fact that other properties are shared or not. On the contrary, an exemplar based representation includes information that is not relevant from this point of view (typically, information that idiosyncratically concerns specific individuals). As a consequence, the computation of similarity is assumed to be *non-linear*: an attribute that is shared by the target and by some exemplar is considered to be relevant only if other properties are also shared.

Prototypes and exemplar based approaches involve also different assumptions concerning processing and memory costs. According to the exemplar models, a category is mentally represented by storing in our long term memory many representations of category members; according to prototype theorists, only some parameters are stored, which summarize the features of a typical representative of the category. As a consequence, on the one hand, prototypes are synthetic representations that occupy a smaller memory space. On the other hand, the process of creating a prototype requires more time and computational effort if compared to the mere storage of knowledge about exemplars, which is computationally more parsimonious, since no abstraction is needed.

4 HYBRID PROTOTYPE-EXEMPLAR REPRESENTATIONS

Given the evidence presented in the above section, it is likely, in our opinion, that a dual, prototype and exemplar based, representation of concepts could turn out to be useful for the representation of non classical concepts in ontological knowledge bases also from a technological point of view.

In the first place, there are kinds of concepts that seem to be more suited to be represented in terms of exemplars, and concepts that seem to be more suited to be represented in terms of prototypes. For example, in the case of concepts with a small number of instances, which are very different from one another, a representation in terms of exemplars should be more convenient. An exemplar based representation could be more suitable also for non linearly separable concepts (see the previous section).

On the other hand, for concepts with a large number of very similar instances, a representation based on prototypes seems to be more appropriate. Consider for example an artificial system that deals with apples (for example a fruit picking robot, or a system for the management of a fruit and vegetable market). Since it is no likely that a definition based on necessary/sufficient conditions is available or adequate for the concept APPLE, then the system must incorporate some form of representation that exhibits typicality effects. But probably an exemplar based representation is not convenient in this case: the systems has to do with thousands of apples, which are all very similar one another. A prototype would be a much more natural solution.

In many cases, the presence of both a prototype and an exemplar based representation seems to be appropriate. Let us consider the concept BIRD. And let us suppose that a certain number of individuals b_1, …., b_n are known by the systems to be instances of BIRD (i.e., the system knows *for sure* that b_1, …., b_n are birds). Let us suppose also that one of these b_i's (say, b_k) is a penguin.

Then, a prototype P_{BIRD} is extracted from exemplars b_1, …., b_n, and it is associated with the concept BIRD. Exemplar b_k concurs to the extraction of the prototype, but, since penguins are rather atypical birds, it will result to be rather dissimilar from P_{BIRD}. Let us suppose now that a new exemplar b_h of penguin must be categorized. If the categorization process were based only on the comparison between the target and the prototype, then b_h (which in its turn is rather dissimilar from P_{BIRD}) would be categorized as a bird only with a low degree of confidence, in spite of the fact that penguins are birds in all respects. On the other hand, let us suppose that the process of categorization takes advantage also of a comparison with known exemplars. In this case, b_h, due to its high degree of similarity to b_k, will be categorized as a bird with full confidence. Therefore, even if a prototype for a given concept is available, knowledge of specific exemplars should be valuable in many tasks involving conceptual knowledge. On the other hand, the prototype should be useful in many other situations.

5 A HYBRID PROTOTYPE-EXEMPLAR ARCHITECTURE

In this section we outline the proposal of a possible architecture for concept representation, which takes advantage of the suggestions presented in the sections above. It is based on a hybrid approach, and combines a component based on a Description Logic (DL) with a further component that implements prototypical representations.

Concepts in the DL component are represented as in fig. 2. As usual, every concept can be subsumed by a certain number of superconcepts, and it can be characterised by means of a number of attributes, which relate it to other concepts in the knowledge base. Restrictions on the number of possible fillers can be associated to each attribute. Given a concept, its attributes and its concept/superconcept relations express necessary conditions for it. DL formalisms make it possible to specify which of these necessary conditions also count as sufficient conditions.

Since in this component only necessary/sufficient condition can be expressed, here concepts can be represented only in classical terms: no exceptions and no prototypical effects are allowed. Concepts can have any number of individual instances, that are represented as individual concepts in the taxonomy.

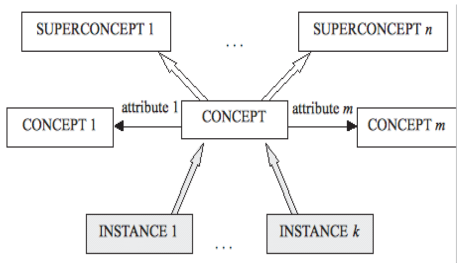

Figure 2: A concept in the DL component.

As an example, consider the fragment of network shown in fig. 3.

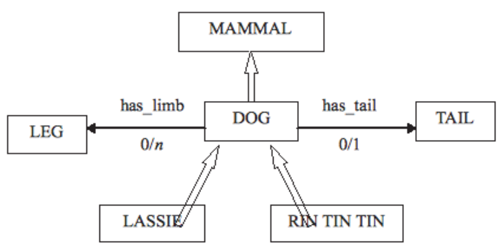

Figure 3: An example of concept.

Here the concept DOG is represented as a subconcept of MAMMAL. Since DL networks can express only necessary and/or sufficient conditions, some details of the representation are very loose. For example, according to fig. 3, a DOG may or may not have a tail (this is the expressed by the number restriction 0/1 imposed on the attribute *has_tail*), and has an unspecified number of limbs (since some dogs could have lost limbs, and teratological dogs could have more than four legs). LASSIE and RIN TIN TIN are represented as individual instances of DOG (of course, concepts describing individual instances can be further detailed, fully specifying for example the values of the attributes inherited from parent concepts).

Prototypes describing typical instances of concepts are represented as data structures that are external to the DL knowledge base. Such structures could, for example, be lists of (possibly weighted) attribute/value pairs that are linked to the corresponding concept. Some attributes of the list should correspond to attributes of the DL concept, which value can be further specified at this level. For example, the prototypical dog is described as having a tail, and exactly four legs. Other attributes of the prototype could have no counterpart in the corresponding DL concept.

As far as the exemplar-based component of the representations is concerned, exemplars are directly represented in the DL knowledge base as instances of concepts. (It may also happen that some information concerning exemplars is represented outside the DL component, in the form of Linked Data. Typically, this could be the case of “non symbolic” information, such as images, sounds, etc.).

It must be noted that prototypical information about concepts (either stored in the form of prototypes or extracted from the representation of exemplars) extends the information coded within the DL formalism. The semantic network provides necessary and/or sufficient conditions for the application of concepts, as a consequence, such conditions hold for every instance of concepts, and cannot be violated by any specific exemplar. So, what can be inferred on the basis of prototypical knowledge can extend, but can in no way conflict with what can be deduced from the DL based component.

6 CONCLUSIONS

In conclusion, we assume that a hybrid prototype/exemplar based representation of non classical concepts could make ontological representation of common-sense concepts more flexible and realistic, thus avoiding at the same time some frequent misuses of DL formalisms.

As a further development of the work presented here, we are currently investigating the possibility of adopting conceptual spaces (Gärdenfors, 2000) as an adequate framework for representing both prototypes and exemplars in many different contexts. Gärdenfors (2004) and others (Adams and Raubal, 2009) proposed conceptual spaces as a tool for representing knowledge in the semantic web. From our point of view, conceptual spaces could offer a common, computational framework do develop our proposal of representing concepts in terms of both prototypes and exemplars.

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