Formalizing Typicality of Objects and Context-sensitivity in Ontologies

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ABSTRACT

In multiagent systems ontologies are essential because they facilitate tasks like communications and reasoning. In this paper, inspired by studies in cognitive psychology, we present a theoretical framework of ontologies that model concepts and properties in a way that typicality of objects can be reflected, and in which context plays a major role in determining the interpretation of the concepts. Typicality is a very common phenomenon observed in different cognitive tasks, while context has been proved to have significant influences on reasoning and categorization. This framework brings together these issues and gives a formal representation of context-sensitive ontologies.

Categories and Subject Descriptors

I.2.4 [**Artificial Intelligence**]: Knowledge Representation Formalisms and Methods—*semantic networks*

General Terms

Human Factors, Theory

Keywords

Semantic Web, Ontologies, Agent Communications, Context

1. INTRODUCTION

With the development of the Semantic Web [3], multiagent systems are expected to play a more essential role in information processing. Ontology [7] also becomes more important because it specifies the definitions of and relations between different concepts. In this paper, we focus on two problems of the Semantic Web. The first problem is the representation of fuzzy concepts and graded membership of instances in ontologies, while the second problem is categorization and forming of taxonomies of concepts in different contexts. We try to solve the problems by proposing a framework for context-sensitive ontologies.

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2. TYPICALITY AND CONTEXT

2.1 Prototype View and Typicality

Concepts are usually defined as crisp sets of objects in ontologies [11]. However, graded membership in concepts is found to be very common [8]. The *prototype view of concepts* [9] suggests that a concept is represented by a prototype which has all the salient properties of the objects that are classified to this concept. The term *typicality* refers to the degree that an object is considered as a member of a concept, and is determined by the number of matching properties of the object and the concept prototype [8, 9]. Moreover properties that are not necessarily in the definition of a concept (*non-necessary properties*) may also affect typicality of an object.

2.2 Context and Context Effect

In general *context* refers to the situation in which an event happens or an action is taken, or the surroundings that help to understand a particular concept. In this paper, we focus on its role in categorization, since this is a major task in the Semantic Web. According to [1], categorizations depends on the circumstance and perspective. In cognitive psychology, the term "context effect" [5] is used to refer to the influence of context in cognitive tasks. Barsalou [2] suggested that properties of a concept can be classified as context-independent or context-dependent. Roth and Shoben [10] also investigated the effect of context in categorization, and suggested context causes a re-weighing of the importance of the properties in a concept and resulting in a different categorization.

3. A COGNITIVE MODEL FOR CONTEXT-SENSITIVE ONTOLOGIES

Inspired by research on the prototype view and context effect, we propose a cognitive model of concepts which takes into account the calculation of typicality of instances, and propose a framework in which categorization of instances are dependent on the context.

3.1 Definition of an Ontology

Ontology is defined as an explicit specification of conceptualization [6]. Here we define an ontology O as a four-tuple

$O = (C, P, I, R)$, where C is a set of concepts, P is a set of properties of the concepts, I is a set of data instances, and lastly R is a set of rules, propositions or axioms.

3.2 Concepts and Properties

In this model, each concept is basically characterized by a set of properties which are singly necessary and jointly sufficient. In addition, a weight is associated with each property in a concept to reflect its importance. Each instance possesses a set of properties and a value is used to indicate the degree to which it possesses each property.

Definition 1. A **concept** $c \in C$ is a fuzzy subset of I, with a membership function μ_c assigning each instance $a \in I$ a membership grade in this concept.

3.3 Characteristic Vector, Property Vector and Subsumption of Concepts

We propose two data structures to represent how properties characterize concepts, and how individuals possess different properties. A *characteristic vector* of a concept is defined as a vector of real numbers in the range of 0 to 1, in which each element corresponds to the weight of a property.

Definition 2. A **characteristic vector** $\vec{c}_c$ of a concept c is a vector of real numbers, $\vec{c}_c = (c_{c,1}, c_{c,2}, ..., c_{c,n}), 0 \leq c_{c,i} \leq 1$.

A *property vector* of an individual is a vector of real numbers, in which each element corresponds to the degree to which the individual possesses a property.

Definition 3. The **property vector** $\vec{p}_a$ of an individual a is a vector of real numbers, $\vec{p}_a = (p_{a,1}, p_{a,2}, ..., p_{a,n}), 0 \leq p_{a,i} \leq 1$.

In addition, we have the following definitions concerning the concept subsumption relations.

Definition 4. For two concepts c and d, c is said to be **subsumed by** d, denoted by $c \sqsubseteq d$, if and only if $c_{c,i} \geq c_{d,i}$ for all $i = 1, 2, ..., n$.

Definition 5. If $c \sqsubseteq d$, then c is said to be a **sub-concept** of d, and d is said to be a **super-concept** of c.

Definition 6. The set of **defining properties** of c is the set which consists of properties having weights greater than zero in the characteristic vector of a concept c.

Definition 7. The set of **properties possessed by** a is the set which consists of properties having a degree greater than zero in the property vector of an individual a.

3.4 Likeliness of an Individual in a Concept

Likeliness of an individual refers to the degree that an individual is an instance of a concept according to the *defining properties* of a concept. This can be considered as the generalization of the crisp membership in existing ontological frameworks, and is similar to the fuzzy membership grade in fuzzy ontologies like [13]. A suitable formula for calculating likeliness should satisfy the following axioms.

Axiom 1. *An individual a has a degree of likeliness of 1 in a concept c if and only if $c_{a,i} > 0 \rightarrow p_{a,i} = 1$ for all $i = 1, 2, ..., n$.*

Axiom 2. *An individual a has a degree of likeliness of 0 in a concept c if and only if $c_{a,i} > 0$ and $p_{a,i} = 0$ for some $i \in [1, n]$.*

Axiom 3. *For a concept c, and two individuals a and b, if for some j such that $c_{c,j} > 0$, $p_{a,j} > p_{b,j}$ and $p_{a,i} = p_{b,i}$ for all $i \neq j$, then $\mu_c(a) > \mu_c(b)$.*

Axiom 4. *For two concepts c and d, and an individuals a, if for some j such that $c_{c,j} > c_{d,j} > 0$, $p_{a,j} > 0$ and $c_{c,i} = c_{d,i}$ for all $i \neq j$, then $\mu_d(a) > \mu_c(a)$.*

Axiom 5. *For two concepts c and d such that c is a sub-concept of d, the degree of likeliness of an individual a must satisfy $\mu_c(a) \leq \mu_d(a)$.*

A possible function for calculating likeliness is

$$\mu_c(a) = \min_i \{l_i\} \tag{1}$$

where

$$l_i = \begin{cases} p_{a,i} + (1 - c_{c,i}) \times (1 - p_{a,i}) & \text{if } c_{c,i} > 0, p_{a,i} > 0 \\ 0 & \text{if } c_{c,i} > 0, p_{a,i} = 0 \\ 1 & \text{if } c_{c,i} = 0 \end{cases}$$

3.5 Prototype Vector and Typicality

Typicality is a measure of an individual's degree of membership in a concept depending on properties (both necessary and non-necessary) that are shared by most of the instances of the concept. The characteristic vector cannot handle typicality because it only contains information of necessary properties. Thus we introduce here the *prototype vector*. To calculate typicality of an instance, we construct a prototype for the concept, in the form of a *prototype vector*.

Definition 8. The **prototype vector** $\vec{t}_c$ of a concept c is a vector of real numbers, $\vec{t}_c = (t_{c,1}, t_{c,2}, ..., t_{c,n}), 0 \leq t_{c,i} \leq 1$, and is determined by the following equation:

$$\vec{t}_c = \frac{1}{|S|} \sum_{s \in S} \vec{c}_s$$

where S is the set of sub-concepts of c.

Typicality of an instance is determined by a "*weighted feature (property) sum*" [12]. This involves matching the properties in the prototype vector of a concept and the property vector of an individual. The typicality function of a concept, τ_c, should satisfy the following axioms.

Axiom 6. *An individual a has a degree of typicality of 1 in a concept c if and only if $t_{c,i} > 0 \rightarrow p_{a,i} = 1$ for $i = 1, 2, ..., n$.*

Axiom 7. *An individual a has a degree of typicality of 0 in a concept c if and only if $t_{c,i} > 0 \rightarrow p_{a,i} = 0$ for $i = 1, 2, ..., n$.*

Axiom 8. *For a concept c, and two individuals a and b, if for some j such that $t_{c,j} > 0$, $p_{a,j} > p_{b,j} > 0$ and $p_{a,i} = p_{b,i}$ for all $i \neq j$, then $\tau_c(a) > \tau_c(b)$.*

Axiom 9. *For a concept c, and two individuals a and b, if for some j such that $t_{c,j} > 0$, $p_{a,j} > p_{b,j} = 0$ and $p_{a,i} = p_{b,i}$ for all $i \neq j$, then $\tau_c(a) > \tau_c(b)$.*

AXIOM 10. *For two concepts c and d, and an individuals a, if for some j such that $t_{c,j} > t_{d,j} > 0$, $p_{a,j} > 0$ and $t_{c,i} = t_{d,i}$ for all $i \neq j$, then $\tau_d(a) > \tau_c(a)$.*

Here, we present a possible function for calculating an individual's typicality in a concept. The typicality of an individual a of a concept c, denoted by $\tau_c(a)$ is given by:

$$\tau_c(a) = \frac{\vec{p}_a \cdot \vec{t}_c}{\sum_{i=1}^{n} t_{c,i}} \quad (2)$$

4. CONTEXT IN CATEGORIZATION

The model described above serves as a basis for formalizing context in ontology. We consider contexts as different conditions which cause an agent to process information thereafter with different perspectives, and focuses on different properties of a concept.

4.1 Formal Definitions

We define a context x as a collection of propositions, objects and concepts perceived by an agent in the Semantic Web environment.

Definition 9. A **context** x is a three-tuple $\langle N_r, N_c, N_i \rangle$, where $N_r \subseteq R$, $N_c \subseteq C$ and $N_i \subseteq I$.

When an agent perceives a particular context, the agent forms a certain perspective, which is a certain view point on the concepts and individuals. We define perspective as a view point from which an agent assigns different weights to properties in concepts to reflect its foci on certain properties.

Definition 10. A **perspective** v is a mapping from the set $C \times P$ into the set of real numbers in the range 0 to 1, which represents the weights of the properties in the concepts: $v : C \times P \longrightarrow [0, 1]$.

Furthermore, we define the function *View* that maps a context to a perspective formed in an agent.

Definition 11. Let X be the set of contexts and V be the set of perspectives, the function ***View*** is a mapping from X to V: $View : X \longrightarrow V$.

4.2 Contextualized Ontology

After an agent has chosen a perspective according to the context, the agent forms a context-sensitive ontology by applying the weights to the properties in concepts. This can be formalized by a set of interpretations similar to those in description logics [4]. An interpretation assigns to each concept a characteristic vector which contains the corresponding weights of the properties according to the perspective.

Definition 12. An **interpretation** for context i, m_i, consists of a domain Δ_i and an interpretation function $\mathcal{I}_i$: $m_i = \langle \Delta_i, \mathcal{I}_i \rangle$, where Δ_i refers to the domain and $\mathcal{I}_i$ is an interpretation function.

The interpretation function $\mathcal{I}_i$ is a function that maps each concept $c \in C$ to a fuzzy subset of I, and assign a characteristic vector to the concept c. $\mu_{c,i}$ is the membership function of c in the context represented by interpretation m_i. On the other hand, the typicality of an individual can be different due to the different weights of the properties. We use $\tau_{c,i}(a)$ to denote the typicality of individual a in concept c under the interpretation m_i.

4.3 Contextual Subsumption Relations

A hierarchy of concept can be constructed by determining concept subsumption relations. Once contexts are modeled, a subsumption relation between concept c and d, say $c \sqsubseteq d$, may only hold within a certain context.

Definition 13. For two concepts c and d, c is said to be **subsumed by** d under the interpretation m_x, denoted by $c \sqsubseteq_{m_x} d$, if and only if $c_{c,j} \geq c_{d,j}$ for all $j = 1, 2, ..., n$.

5. CONCLUSION AND FUTURE WORKS

This paper attempts to provide a theoretical framework of context-sensitive ontology, which handles both fuzzy membership grades, typicality of objects, and models context so that agents are able to interpret concepts according to the current situations. Future works on this framework include investigation of how the function *View* can be implemented such as by using some learning algorithms, and extension of the framework to handle other aspects of context such as disambiguating terms with multiple meanings.

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