Challenges and Directions for Knowledge Management in Networks of Aligned Ontologies

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Abstract: Next generation Semantic Web applications have to deal with the real world scenarios of heterogeneous and distributed knowledge in which collaboration based on knowledge is required. Knowledge is encoded in semantically rich structures, namely ontologies, while simultaneously, semantic links, that is, alignments are needed for their successful collaboration. The dynamic unification of a set of ontologies linked by alignments comprises a network of aligned ontologies. This paper presents some theoretical issues related to the area of networks of aligned ontologies, aiming at improving practical research directions. More specifically, we consider here the need, challenges and some guidelines for knowledge representation, management and propagation within networks of aligned ontologies.

1 INTRODUCTION

Ontologies (Chandrasekaran et al., 1999), (Fonseca, 2007) have been traditionally designed and applied in applications where knowledge representation is needed. These ontologies have been constructed as stand-alone artifacts. For more complex applications, where knowledge management is required, ontologies might relate to each other by designing correspondences between entities of different ontologies, that is, by constructing alignments (Euzenat and Shvaiko, 2007). These alignments constitute the semantic linking among corresponding ontologies and lead to the development of networked ontologies.

Towards this end, two trends within the ontology field have emerged: the ontology networks and the networks of aligned ontologies. An ontology network, or a network of ontologies is defined as a collection of ontologies related together via a variety of different meta-relationships, such as mapping, modularization, version and dependency relationships (Diaz et al., 2011), (Suarez-Figueroa et al., 2012), whereas a network of aligned ontologies is defined as a set of ontologies interconnected with alignments (Euzenat, 2011). Both concepts are used to organize different types of content by integrating heterogeneous knowledge sources.

The increasing interest in both ontology networks and networks of aligned ontologies has a crucial impact on scientific research, regarding many aspects of ontology engineering, ontology alignment, inconsistency detecting, etc. So far, work on ontology networks mainly refers to how techniques such as reuse, modularity and modification are applied on ontologies (Suarez-Figueroa, 2010), while work on networks of aligned ontologies mainly deals with consistency checking methods of reasoning (Fionda and Pirro, 2011).

In this paper, we focus on networks of aligned ontologies, considering research topics such as knowledge representation, knowledge management and knowledge propagation within them. The main idea behind the appearance of networks of aligned ontologies is the ability to share and reuse ontologies and alignments, since designing and maintaining them is deemed to be a time-consuming and labor intensive task (Grau et al., 2008), (Beisswanger and Hahn, 2012).

The remainder of this paper is organized as follows. Section 2 gives an overview of the knowledge representation through ontologies within networks of aligned ontologies, by stating the challenges that the ontology engineering community faces. Section 3 underlines the need for manipulating changes in networks of aligned ontologies, in order to correctly manage the knowledge within them. Section 4 describes the need for propagating knowledge within networks of aligned ontologies and suggests a formal model for

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achieving this task. Finally, Section 5 deals with some conclusions and future work.

2 KNOWLEDGE REPRESENTATION IN NETWORKS OF ALIGNED ONTOLOGIES

Knowledge representation in networks of aligned ontologies involves ontologies that represent different pieces of knowledge and alignments that represent the semantic correlation of the corresponding ontologies.

2.1 Need

Applications in open, dynamic and distributed environments, such as the Semantic Web need to share resources. These applications involve autonomous entities which have been designed independently (Euzenat et al., 2008), (Pruvost et al., 2009) thus facing a high level of heterogeneity. On the one hand, this is desirable, as it allows the involved parties to structure knowledge in a way fitting their needs best, e.g., regarding a specific application. On the other hand, this becomes problematic, as it impedes the involved parties' communication because knowledge of the resources is encoded in a variety of ways. One aspect of overcoming heterogeneity in order for the involved entities to interoperate in these environments, is an explicit and semantically rich representation of knowledge through ontologies. Ontologies aim at capturing domain knowledge in an explicit way and they provide a consensual understanding of the domain (de Bruijn, 2003). Because it is impractical for all the involved entities to share a unique and global ontology, a plethora of individual ontologies have recently emerged, some of them representing overlapping content (Euzenat et al., 2008). Thus, the fact of using different ontologies increases heterogeneity problems to a different level.

Semantic alignment between ontologies is a solution to the heterogeneity problem. It can be considered as the result of the ontology matching process, which deals with finding the correspondences between semantically related entities of different ontologies (Ehrig, 2007). The existence of a semantic alignment between ontologies is a necessary precondition to establish interoperability between the involved entities using different individual ontologies. Moreover, human users want to access the knowledge represented in numerous different ontologies in order to ease the tasks of searching, or browsing. In addition, new knowledge can be inferred by combining the information contained in the various ontologies. Thus, ontology alignment is a crucial issue to resolve in any application involving more than one entities, or parties, where semantic heterogeneity is an intrinsic problem (Shvaiko and Euzenat, 2013).

Once semantic alignments have been established between individual ontologies, a network of linked ontologies can be created. In this setting, ontologies represent different knowledge sources participating in the network, and alignments represent the semantic links between these sources.

2.2 Challenge

Constructing networks of aligned ontologies typically consists of dynamically assembling their components, that is, ontologies and alignments, in such a way that the overall structure entails new knowledge. Since such components are authored in different context, unaware of what other a posteriori formal knowledge they will be combined with, the challenge is to provide guidance for separately engineering ontologies and alignments, instead of proposing a unified model for the construction of networks of aligned ontologies. There are also many challenges regarding ontology engineering, especially ontology reuse. Moreover, there is little support, in the ontology matching process, regarding the selection of suitable matchers in order to produce correct alignments.

2.3 Suggestion

In this perspective, on the one hand, an ontology engineering approach is needed, which must emphasize on the availability of knowledge sources to be used (Terrazas, 2011). On the other hand, an ontology alignment strategy with emphasis on the selection of the suitable matchers and the involvement of a trusted third party in order to ensure the generation of reliable alignments (Kameas and Seremeti, 2011), is needed.

3 KNOWLEDGE MANAGEMENT IN NETWORKS OF ALIGNED ONTOLOGIES

Knowledge management in networks of aligned ontologies consists of managing changes that occurred in their constituents (ontologies and alignments).

3.1 Need

Networks of aligned ontologies are defined as directed graphs, consisting of vertices representing heterogeneous ontologies and edges representing alignments among them. Both their autonomous components, which have been designed independently, are carriers of meaning. On the one hand, ontologies convey semantics, since they are defined as the formal conceptualizations of a domain of interest (Studer et al., 1998). On the other hand, alignments are defined as the links that semantically relate two formal conceptualizations (Scharffe et al., 2008). As both components describe parts of the world and their interconnections, they may undergo changes, due to the dynamic nature of the describing world. These changes, despite the fact that they may occur in isolated components, they may result in an inconsistent state for the overall network of interlinked components.

3.2 Challenge

The facts that new ontologies can be embedded in a network of already aligned ones, or can be removed from such a network and that ontologies and/or alignments between them have to be kept up to date in changing application contexts, are some of the factors that are involved in the definition of the dynamic engineering of networks of aligned ontologies. Moreover, in order to take into account the fact that making changes based on isolated entities, while ignoring the semantic interrelations among them, may result in an inconsistent state for the underlying semantic model, we consider a twofold view of such networks: a local and a global one. The local view refers to isolated entities, that is, ontologies and alignments, while the global one refers to the context in which the separate components are interconnected in a way that explicitly characterizes the semantics of a specific application. Thus, to define change operations in networks of aligned ontologies, one has to take into account, not only all the possible effects a change can have on its separate components, but also its influence on the hypostasis of the networks themselves.

3.3 Suggestion

With respect to the aforementioned views of a network of aligned ontologies, we claim that significant improvements in managing it can be obtained, by addressing important challenges for manipulating changes in three interrelated levels:

- The ontology level, which represents changes in the ontologies, namely the changes in their domain of usage, (since most domains have a dynamic nature), changes in their level of formality and/or their level of granularity. More precisely, Klein (Klein, 2004) distinguishes among three kinds of changes that may occur within an ontology, i.e., conceptual, specification and representation changes;
- The alignment level, which represents changes in the definition of alignments between the same pair of ontologies, for example by applying a different matching algorithm, or by using an alternative representation language (Ehrig, 2007);
- The network level, which represents changes in the number and the content of the ontologies that participate in a network of aligned ontologies. For example, a new ontology must be added to a network of previous aligned ontologies, or must be removed from the network, according to the requirements imposed by a specific application (Kameas and Seremeti, 2011).

From an engineering point of view, changes at the ontology level refer to the ontology evolution and versioning processes (Yildiz, 2006), (Jaziri, 2009), which are based on discovering semantic relations among entities of two versions of the same ontology and require the ontology alignment process. Changes at the alignment level refer to the alignment versioning process (Euzenat and Shvaiko, 2007), which aims at finding out relations among two versions of the same alignment, while, changes at the network level require the definition of an ontology alignment composition operator (Zimmermann and Le Duc, 2008).

4 KNOWLEDGE PROPAGATION IN NETWORKS OF ALIGNED ONTOLOGIES

A network of aligned ontologies is a distributed system, whose components (constituent ontologies) are interacting and interoperating, the result of this interaction being, either the extension of local assertions, which are valid within each individual ontology, to global assertions holding between remote ontology entities through a network path, or to local assertions holding between local entities of an ontology, but induced by remote ontologies, through a cycle. In order to describe this interaction, we use knowledge propagation.

4.1 Need

Consider for example the network of Figure 1, where the relationships between entities a_i, b_i, c_i, d_i of ontologies O_1, O_2 and O_3 are considered to be, either subsumption ($\leq$) or disjointness ($\perp$) ones. We also consider the alignments A_{12} (between entities of O_1 and O_2), A_{23} (between O_2 and O_3) and A_{31} (between O_3 and O_1), where the relations involved between entities belonging to different ontologies are subsumption relationships. Induced relations, resulting from composition of relations, are marked with dotted lines. In this network, new relations can be deduced, for example by either relating ontological entities belonging to remote ontologies O_1 and O_3 through the particular path $O_1 - A_{12} - O_2 - A_{23} - O_3$ of ontologies and alignments in the network, or by relating ontological entities belonging to the same ontology, but through a particular path forming a loop starting and ending at this specific ontology. This is for example the case for the loop $O_3 - A_{31} - O_1 - A_{12} - O_2 - A_{23} - O_3$, where the relations revealed make apparent consistency problems emerging from the network induced relations, as will be evident in Section 4.3.

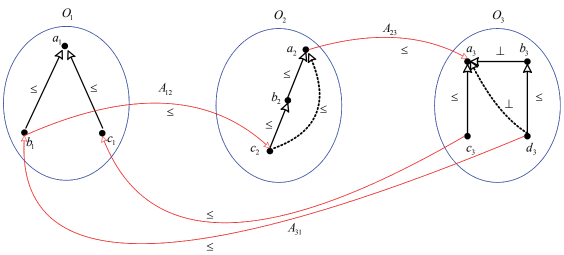

Figure 1: An example of a network of aligned ontologies.

4.2 Challenge

Thus, a crucial issue is: while propagating local knowledge through the network, one should be able to retain the consistency of the whole network and extract meaningful results from the global knowledge emerging from a particular network of aligned ontologies.

4.3 Suggestion

Significant improvements can be obtained only by addressing the important issue of formalizing the basic building blocks of networks of aligned ontologies (constituent ontologies and alignments) and the propagation of knowledge within them, in a way independent from their language representation and implementation. In order to be able to propagate relations in a network of ontologies and alignments, we define a matrix representation of an ontology, or an alignment, where we represent the ontology, or alignment by a so-called propagation matrix.

This representation depends strongly on the specific position that an ontology occupies in a chain of ontologies and alignments that forms a path of consecutive ontologies and alignments in the network More specifically, we differentiate the representation according to whether an ontology is a starting node involved only in a succeeding alignment, or a transition node involved in both a preceding and a succeeding alignments, or, finally, an ending node involved only in a preceding alignment. Alignments can also be represented in an analogous manner as the one adopted for ontologies, since an alignment between two ontologies relates entities of the preceding source ontology to entities of the succeeding target ontology.

In these propagation matrix representations, we express local relations between ontology entities that can be further propagated through the path. More precisely, for ontologies that are starting nodes in the path, these are local relations further propagated in the network through the succeeding alignment; for ontologies that are transition nodes these are local relations that can be composed with relations arriving to the ontology via the preceding alignment and can be further propagated in the network via the succeeding alignment; for ontologies that act as ending nodes, these are local relations that can be composed with relations arriving to the ontology via the preceding alignment. In general, the element (k,l) of the propagation matrix representation corresponds to the composition of relations holding along all the paths connecting the source ontology entity k to the target ontology entity l. In the l^{th} column of the propagation matrix we find all the compositions of relations along all the paths having as source object some entity of the ontology and having l as the target entity. This corresponds to all the incoming arrows to object l, and can be represented by the notion of contravariant representable functors, a construct in the formalism based on Category Theory (Barr and Wells, 2012). A category is a structure consisting of a collection of objects and a collection of morphisms between objects, equipped with an associative composition operator and a unique morphism associated to each object, acting as the unit of the composition. Given a category and a fixed object, say A, in that category, the contravariant representable functor maps a certain object, say C, in the category, to the set of all morphisms from C to A, i.e. it refers to all incoming morphisms to the fixed object A and categorizes them according to the object which is the origin of the morphism.

Category Theory has been extensively used as an appropriate framework for the formalization of ontologies and their operations (Zimmermann et al., 2006), (Euzenat, 2011), (Diskin and Maibaum, 2012), (Spivak and Kent, 2012), where "local truth" vs. "global truth" in a network is studied by defining and combining several categorical structures.The propagation matrices can be combined along sequential or parallel paths, by defining adequate operators. For this purpose we define a sequential composition operator denoted as $*$ and a parallel composition operator denoted as $+$. The sequential composition operator resembles the usual matrix multiplication operator, where multiplication has been substituted by relation composition and addition by the disjunction of relations. The sequential composition operator can be applied repeatedly along a chain of ontologies and alignments that define a path in a network of ontologies, in order to propagate local knowledge to global one. When two ontologies in the network are connected through a number of different paths, the parallel composition operator is used. This increases expressiveness, since now entities can be related through any possible relation belonging to a set of available ones composable over a suitable algebra of binary relations, and which could be more elaborate than the usual subsumption relations.

In the example of Figure 1, we calculate the propagation matrix through the path (cycle) $O_3 - A_{31} - O_1 - A_{12} - O_2 - A_{23} - O_3$ by repeatedly applying the sequential operator over the individual propagation matrices, respectively:

$$\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} * \begin{bmatrix} 0 & \leq \\ \leq & 0 \end{bmatrix} * \begin{bmatrix} 1 \\ 0 \end{bmatrix} * [\leq] * [\leq] * [\leq] * [1 \quad 0 \quad 0 \quad 0]$$

Since for example O_3 is a starting node in this path, its respective propagation matrix

$$\begin{array}{c|c} & c_3 \quad d_3 \\ \hline a_3 & \\ b_3 & \\ c_3 & \\ d_3 & \end{array} \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$$

expresses the relations between from one part the entities a_3, b_3, c_3, d_3 and from the other part the entities c_3, d_3, these being the only relations that can be further propagated in the network. Concerning the alignment A_{31}, the respective propagation matrix

$$\begin{array}{c|cc} & b_1 & c_1 \\ \hline c_3 & 0 & \leq \\ d_3 & \leq & 0 \end{array}$$

expresses the relations holding between c_3, d_3 of O_3 and b_1, c_1 of O_1. Here, 0 denotes the absence of relation between the respective elements and 1 the unity element of the composition of relations. By adequately composing the binary relations over an adequate algebra of binary relations, one gets:

$$\begin{array}{c|cccc} & a_3 & b_3 & c_3 & d_3 \\ \hline a_3 & 0 & 0 & 0 & 0 \\ b_3 & 0 & 0 & 0 & 0 \\ c_3 & 0 & 0 & 0 & 0 \\ d_3 & \leq & 0 & 0 & 0 \end{array}$$

from where the relation $d_3 \leq a_3$ results. From the local knowledge of ontology O_3, we obtain:

$$\begin{array}{c|cccc} & a_3 & b_3 & c_3 & d_3 \\ \hline a_3 & 1 & 0 & 0 & 0 \\ b_3 & \perp & 1 & 0 & 0 \\ c_3 & \leq & 0 & 1 & 0 \\ d_3 & \perp & \leq & 0 & 1 \end{array}$$

from where the relation $d_3 \perp a_3$ results. When the two propagation matrices are considered conjuctively, the inconsistency between the relations $d_3 \leq a_3$ and $d_3 \perp a_3$ is revealed.

5 CONCLUSIONS AND FUTURE WORK

Ontologies are no longer stand-alone artifacts, but they are linked through alignments in order to support semantically enabled applications. Towards this end, a new trend within the ontology field has emerged: the network of aligned ontologies. The appearance of networks of aligned ontologies is due to the achievements of the ontology community about ontologies and alignments reuse and evolution.

In this paper, we focused on (a) ontologies and alignments as the constituent components of networks of aligned ontologies, in order to obtain knowledge representation within such settings, (b) changes occurred in the ontology, alignment and network level, in order to manage evolving knowledge, and (c) suggesting a mathematical formalization for achieving knowledge propagation, in order to detect inconsistency within them. We presented some challenges with insights on how to approach them, thereby aiming to facilitate the progress in the field.

As far as future research is concerned, we envisage the direction of implementing algorithms based on Category Theory, and especially on contravariant representable functors, for representing, managing and propagating knowledge within networks of aligned ontologies. This will contribute in detecting conceptual errors in order to revise the knowledge emerging from the whole network.

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