Ontology of integration and integration of ontologies

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Abstract

One of the basic problems in the development of techniques for the semantic web is the integration of ontologies. In this paper we deal with a situation where we have various local ontologies, developed independently from each other, and we are required to build an integrated, global ontology as a mean for extracting information from the local ones. In this context, the problem of how to specify the mapping between the global ontology and the local ontologies is a fundamental one, and its solution is essential for establishing an ontology of integration. Description Logics (DLs) are an ideal candidate to formalize ontologies, due to their ability to express complex relationships between concepts. We argue, however, that, for capturing the mapping between different ontologies, the direct use of a DL, even a very expressive one, is not sufficient, and it is necessary to resort to more flexible mechanisms based on the notion of *query*. Also, we elaborate on the observation that, in the semantic web, the case of mutually inconsistent local ontologies will be very common, and we present the basic ideas in order to extend the integration framework with suitable nonmonotonic features for dealing with this case.

1 Introduction

In the last years, Description Logics (DLs) have been successfully applied to semantic data modeling [12, 1, 19, 10], and have been proposed as knowledge representation mechanisms for semantic web applications [16, 3]. The idea behind applying DLs to the semantic web is related to the need of representing and reasoning on ontologies: if ontologies are expressed as DL knowledge bases, then DL reasoning techniques can be used for several services in the design of and the interaction with the semantic web.

One of the basic problems in the development of techniques for the semantic web is the integration of ontologies. Indeed, the web is composed of a variety of information sources, and in order to extract information from such sources, their semantic integration and reconciliation is required. In this paper we deal with a situation where we have various local ontologies, developed independently from each other, and we are required to build an integrated, global ontology as a mean for extracting information from the local ones. Thus, the main purpose of the global ontology is to provide a unified view through which we can query the various local ontologies.

Most of the work carried out on ontologies for the semantic web is on how to build the global ontology on the basis of the local ones. In this paper, we address what we believe is a crucial problem for the semantic web: how do we specify the mapping between the global ontology and the local ontologies. This aspect is the central one if we want to use the global ontology for answering queries in the context of the semantic web. Indeed, we are not simply using the local ontologies as an intermediate step towards the global one. Instead, we are using the global ontology for accessing information in the local ones. It is our opinion that, although the problem of specifying the mapping between the global and the local ontologies is at the heart of integration in the web, it is not deeply investigated yet. In a sense, we still lack a full understanding of an *ontology of integration*, which is very important in order to develop suitable techniques for the *integration of ontologies*.

DLs have proved to be able to capture conceptual and semantic data models used in databases and software engineering, such as Entity-Relationship diagrams, and UML class diagrams [7, 4]. In addition, the ability to express complex relationships between concepts make them an ideal candidate to formalize ontologies. For example, the Ontology Inference Layer (OIL) [16, 3] is based on a restricted form of the expressive and decidable DLs studied in [14, 5, 15, 6]. We argue, however, that even such expressive DLs are not sufficient for information integration in the semantic web. In a real world setting, different ontologies are build by different organizations for different purposes. Hence one should expect the same information to be represented in different forms and with different levels of abstraction in the various ontologies. When mapping concepts in the various ontologies to each other, it is very likely that a concept in one ontology corresponds to a *query* (i.e., a *view*) over the other ontologies. Observe that here the notion of "query" is a crucial one. DLs can be thought of as first-order languages (possibly extended with fixpoints) with limitations on the use of variables [2]. Exactly such limitations make even the most expressive DLs quite poor as query languages. Therefore, to express mappings among concepts in different ontologies, suitable query languages should be added to DLs, and considered in the various reasoning tasks, in the spirit of [6, 8].

Our contribution in this paper is to present a general framework for an ontology of integration where ontologies are expressed as DL knowledge bases, and mappings between ontologies are expressed through suitable mechanisms based on queries. Also, we elaborate on the observation that, in the semantic web, the case of mutually inconsistent local ontologies will be very common, and we present the basic ideas in order to extend the framework with suitable nonmonotonic features for dealing with this case.

The paper is organized as follows. In the next section we set up a formal framework for ontology integration, based on first order logic. In Section 3, we present our basic ideas for an ontology of integration, and in particular we discuss three basic means for specifying the mapping between the global and the local ontologies. In Section 4 we extend the framework in order to cope with the problem of integrating incoherent local ontologies. Section 5 concludes the paper.

2 Ontology of integration: The framework

In this section we set up a formal framework for *ontology integration systems* (OISs). We argue that this framework provides the basis of an *ontology of integration*. For the sake of simplicity, we will refer to a simplified framework, where the components of an OIS are the global ontology, the local ontologies, and the mapping between the two. We call such systems "one-layered". More complex situations can be modeled by extending the framework in order to represent, for example, mappings between local ontologies (in the spirit of [13, 9]), or global ontologies that act as local ones with respect to another layer.

In what follows, one of the main aspects is the definition of the semantics of both the OIS, and of queries posed to the global ontology. For keeping things simple, we will use in the following a unique semantic domain Δ, composed of a fixed, infinite set of symbols.

Formally, an OIS $\mathcal{O}$ is a triple $\langle \mathcal{G}, \mathcal{S}, \mathcal{M}_{\mathcal{G},\mathcal{S}} \rangle$, where $\mathcal{G}$ is the global ontology, $\mathcal{S}$ is the set of local ontologies, and $\mathcal{M}_{\mathcal{G},\mathcal{S}}$ is the mapping between $\mathcal{G}$ and the local ontologies in $\mathcal{S}$.

The global ontology. We denote with $\mathcal{A}_{\mathcal{G}}$ the alphabet of terms of the global ontology, and we assume that the global ontology $\mathcal{G}$ of an OIS is expressed as a theory (named simply $\mathcal{G}$) in a DL $\mathcal{L}_G$.

The local ontologies. We assume to have a set $\mathcal{S}$ of n local ontologies $\mathcal{S}_1, \ldots, \mathcal{S}_n$. We denote with $\mathcal{A}_{\mathcal{S}_i}$ the alphabet of terms of the local ontology $\mathcal{S}_i$. We also denote with $\mathcal{A}_{\mathcal{S}}$ the union of all the $\mathcal{A}_{\mathcal{S}_i}$'s. We assume that the various $\mathcal{A}_{\mathcal{S}_i}$'s are mutually disjoint, and each one is disjoint from the alphabet $\mathcal{A}_\mathcal{G}$. We assume that each local ontology is expressed as a theory (named simply $\mathcal{S}_i$) in a DL $\mathcal{L}_{\mathcal{S}_i}$, and we use $\mathcal{S}$ to denote the collection of theories $\mathcal{S}_1, \ldots, \mathcal{S}_n$.

The mapping. The mapping $\mathcal{M}_{\mathcal{G},\mathcal{S}}$ is the heart of the OIS, in that it specifies how the concepts[1] in the global ontology and in the local ontologies map to each other. We discuss this aspect more deeply in the next section. Here, we simply assume that $\mathcal{M}_{\mathcal{G},\mathcal{S}}$ is an appropriate specification of how the concepts in the various ontologies map to each other.

The semantics. Intuitively, in specifying the semantics of an OIS, we have to start with a model of the local ontologies, and the crucial point is to specify which are the models of the global ontology. Thus, for assigning semantics to an OIS $\mathcal{O} = \langle \mathcal{G}, \mathcal{S}, \mathcal{M}_{\mathcal{G},\mathcal{S}} \rangle$, we start by considering a *local model* $\mathcal{D}$ for $\mathcal{O}$, i.e., an interpretation that is a model for all the theories of $\mathcal{S}$. We call *global interpretation* for $\mathcal{O}$ any interpretation for $\mathcal{G}$. A global interpretation $\mathcal{I}$ for $\mathcal{O}$ is said to be a *global model for $\mathcal{O}$ wrt $\mathcal{D}$* if:

- $\mathcal{I}$ is a model of $\mathcal{G}$,
- $\mathcal{I}$ satisfies the mapping $\mathcal{M}_{\mathcal{G},\mathcal{S}}$ wrt $\mathcal{D}$.

In the next section, we will come back to the notion of satisfying a mapping wrt a local model. The semantics of $\mathcal{O}$, denoted $sem(\mathcal{O})$, is defined as follows:

$$sem(\mathcal{O}) = \{\, \mathcal{I} \mid \text{there exists a local model } \mathcal{D} \text{ for } \mathcal{O} \text{ s.t. } \mathcal{I} \text{ is a global model for } \mathcal{O} \text{ wrt } \mathcal{D} \,\}$$

Queries. Queries posed to an OIS $\mathcal{O}$ are expressed in terms of a query language $\mathcal{Q}_\mathcal{G}$ over the alphabet $\mathcal{A}_\mathcal{G}$ and are intended to extract a set of tuples of elements of Δ. Thus, every query has an associated arity, and the semantics of a query q of arity n is defined as follows. The answer $q^\mathcal{O}$ of q to $\mathcal{O}$ is the set of tuples

$$q^\mathcal{O} = \{ (c_1, \ldots, c_n) \mid \text{for all } \mathcal{I} \in sem(\mathcal{O}),\ (c_1, \ldots, c_n) \in q^\mathcal{I} \,\}$$

where $q^\mathcal{I}$ denotes the result of evaluating q in the interpretation $\mathcal{I}$.

3 Ontology of integration: The mapping

As we said before, the mapping $\mathcal{M}_{\mathcal{G},\mathcal{S}}$ represents the heart of an OIS $\mathcal{O} = \langle \mathcal{G}, \mathcal{S}, \mathcal{M}_{\mathcal{G},\mathcal{S}} \rangle$. In the usual approaches to ontology integration, the mechanisms

[1] Here and below we use the term "concept" for denoting a concept of the ontology, which in turn can be represented either by a class or by a relation (not necessarily atomic) in DLs.

for specifying the mapping between concepts in different ontologies are limited to expressing direct correspondences between terms. We argue that, in a real-world settings, one needs a much more powerful mechanism. In particular, such a mechanism should allow for mapping a concept in one ontology into a *view*, i.e., a query, over the other ontologies, which acquires the relevant information by navigating and aggregating several concepts.

In this section we base our considerations on these more powerful mechanisms, and we discuss the various ways that one can use for specifying the mapping. The terminology used in this section is inspired by [18, 17], where the focus is on integrating data sources rather than ontologies/theories expressed in DLs.

3.1 Global-centric approach

In the global-centric approach (aka global-as-view approach), we assume we have a query language $\mathcal{V}_\mathcal{S}$ over the alphabet $\mathcal{A}_\mathcal{S}$, and the mapping between the global and the local ontologies is given by associating to each term in the global ontology a *view*, i.e., a query, over the sources. The intended meaning of associating to a term C in $\mathcal{G}$ a query V_s over $\mathcal{S}$, is that such a query represents the best way to characterize the instances of C using the concepts in $\mathcal{S}$. A further mechanism is used to specify if the correspondence between C and the associated view is *sound*, *complete*, or *exact*. Let $\mathcal{D}$ be a local model for $\mathcal{O}$, and $\mathcal{I}$ a global interpretation for $\mathcal{O}$:

- $\mathcal{I}$ satisfies the triple $\langle C, V_s, sound\rangle$ in $\mathcal{M}_{\mathcal{G},\mathcal{S}}$ wrt $\mathcal{D}$, if all the tuples satisfying V_s in $\mathcal{D}$ satisfy C in $\mathcal{I}$,

- $\mathcal{I}$ satisfies the triple $\langle C, V_s, complete\rangle$ in $\mathcal{M}_{\mathcal{G},\mathcal{S}}$ wrt $\mathcal{D}$, if no tuple other than those satisfying V_s in $\mathcal{D}$ satisfies C in $\mathcal{I}$.

- $\mathcal{I}$ satisfies the triple $\langle C, V_s, exact\rangle$ in $\mathcal{M}_{\mathcal{G},\mathcal{S}}$ wrt $\mathcal{D}$, if the set of tuples that satisfy C in $\mathcal{I}$ is exactly the set of tuples satisfying V_s in $\mathcal{D}$.

We say that $\mathcal{I}$ satisfies the mapping $\mathcal{M}_{\mathcal{G},\mathcal{S}}$ wrt $\mathcal{D}$, if $\mathcal{I}$ satisfies every triple in $\mathcal{M}_{\mathcal{G},\mathcal{S}}$ wrt $\mathcal{D}$.

The global-centric approach is the one adopted in most data integration systems. In such systems, sources are databases (in general relational ones), the global ontology is actually a database schema (again, represented in relational form), and the mapping is specified by associating to each relation in the global schema one relational query over the source relations. It is a common opinion that this mechanism allow for a simple query processing strategy, which basically reduces to unfolding the query using the definition specified in the mapping, so as to translate the query in terms of accesses to the sources [21]. Recently, we have showed that in the case where we add constraints (even of a very simple form) to the global schema, query processing becomes harder. In the present framework, since we are considering the integration of ontologies (expressed as DL theories) rather than databases, the problem is even more complex.

3.2 Local-centric approach

In the local-centric approach (aka local-as-view approach), we assume we have a query language $\mathcal{V}_{\mathcal{G}}$ over the alphabet $\mathcal{A}_{\mathcal{G}}$, and the mapping between the global and the local ontologies is given by associating to each term in the local ontologies a *view*, i.e. a query, over the global ontology. Again, the intended meaning of associating to a term C in $\mathcal{S}$ a query V_g over $\mathcal{G}$, is that such query represents the best way to characterize the instances of C using the concepts in $\mathcal{G}$. As in the global-centric approach, the correspondence between C and the associated view can be either sound, complete, or exact. Let $\mathcal{D}$ be a local model for $\mathcal{O}$, and $\mathcal{I}$ a global interpretation for $\mathcal{O}$:

- $\mathcal{I}$ satisfies the triple $\langle V_g, C, \mathit{sound}\rangle$ in $\mathcal{M}_{\mathcal{G},\mathcal{S}}$ wrt $\mathcal{D}$, if all the tuples satisfying C in $\mathcal{D}$ satisfy V_g in $\mathcal{I}$,

- $\mathcal{I}$ satisfies the triple $\langle V_g, C, \mathit{complete}\rangle$ in $\mathcal{M}_{\mathcal{G},\mathcal{S}}$ wrt $\mathcal{D}$, if no tuple other than those satisfying C in $\mathcal{D}$ satisfies V_g in $\mathcal{I}$,

- $\mathcal{I}$ satisfies the triple $\langle V_g, C, \mathit{exact}\rangle$ in $\mathcal{M}_{\mathcal{G},\mathcal{S}}$ wrt $\mathcal{D}$, if the set of tuples that satisfy C in $\mathcal{D}$ is exactly the set of tuples satisfying V_g in $\mathcal{I}$.

As in the global-centric approach, we say that $\mathcal{I}$ satisfies the mapping $\mathcal{M}_{\mathcal{G},\mathcal{S}}$ wrt $\mathcal{D}$, if $\mathcal{I}$ satisfies every triple in $\mathcal{M}_{\mathcal{G},\mathcal{S}}$ wrt $\mathcal{D}$.

Recent research work on data integration follows the local-centric approach [20, 9, 8]. The major challenge of this approach is that in order to answer a query expressed over the global schema, one must be able to reformulate the query in terms of queries to the sources. While in the global-centric approach such a reformulation is guided by the definitions in the mapping, here the problem requires a reasoning step, so as to infer how to use the sources for answering the query [11, 8]. In particular, [8] provides a solution to this problem in the case where the DL used to express the global and local ontologies is $\mathcal{DLR}$, and the query language to express the mapping is union of conjunctive queries.

Many authors point out that, despite its difficulty, the local-centric approach better supports a dynamic environment, where local ontologies can be added to the systems without the need of restructuring the global ontology.

3.3 Unrestricted mapping

In the unrestricted approach, we have both a query language $\mathcal{V}_{\mathcal{S}}$ over the alphabet $\mathcal{A}_{\mathcal{S}}$, and a query language $\mathcal{V}_{\mathcal{G}}$ over the alphabet $\mathcal{A}_{\mathcal{G}}$, and the mapping between the global and the local ontologies is given by relating views over the global ontology to views over the local ontologies. Again, the intended meaning of relating the view V_g over the global ontology to the view V_s over the local ontology is that V_s represents the best way to characterize the objects satisfying V_g in terms of the concepts in $\mathcal{S}$. In other words, in the unrestricted approach we try to combine and extend the representation power of the previous approaches. Analogously to the other cases, the correspondence between V_g and V_s can be characterized as sound, complete, or exact. Let $\mathcal{D}$ be a local model for $\mathcal{O}$, and $\mathcal{I}$ a global interpretation for $\mathcal{O}$:

- $\mathcal{I}$ satisfies the triple $\langle V_g, V_s, \mathit{sound}\rangle$ in $\mathcal{M}_{\mathcal{G},\mathcal{S}}$ wrt $\mathcal{D}$, if all the tuples satisfying satisfying V_s in $\mathcal{D}$ satisfy V_g in $\mathcal{I}$,

- $\mathcal{I}$ satisfies the triple $\langle V_g, V_s, \mathit{complete}\rangle$ in $\mathcal{M}_{\mathcal{G},\mathcal{S}}$ wrt $\mathcal{D}$, if no tuple other than those satisfying V_s in $\mathcal{D}$ satisfy V_g in $\mathcal{I}$,

- $\mathcal{I}$ satisfies the triple $\langle V_g, V_s, \mathit{exact}\rangle$ in $\mathcal{M}_{\mathcal{G},\mathcal{S}}$ wrt $\mathcal{D}$, if the set of tuples that satisfy V_g in $\mathcal{I}$ is exactly the set of tuples satisfying V_s in $\mathcal{D}$.

Again, we say that $\mathcal{I}$ satisfies the mapping $\mathcal{M}_{\mathcal{G},\mathcal{S}}$ wrt $\mathcal{D}$, if $\mathcal{I}$ satisfies every triple in $\mathcal{M}_{\mathcal{G},\mathcal{S}}$ wrt $\mathcal{D}$.

This approach is largely unexplored, mainly because it combines the difficulties of the other ones. However, we argue that, in real world settings, this is the only approach that provides the appropriate expressive power.

4 Beyond first-order logic

According to our definition of an OIS $\mathcal{O}$, it is easy to see that it may happen that no global model for $\mathcal{O}$ exists, even when at least one local model for $\mathcal{O}$ exists. This may happen because knowledge in the various local ontologies cannot be completely reconciled in the global ontology. In the formalization presented in the previous sections, this situation gives rises to an inconsistent OIS $\mathcal{O}$ (i.e., $\mathit{sem}(\mathcal{O}) = \emptyset$), which cannot support query processing.

A more general approach would be to provide a formalization that is able to support query processing even when the local ontologies to be integrated are mutually incoherent. Here, we present a preliminary proposal aiming at this goal.

The basic idea is that given an OIS $\mathcal{O} = \langle \mathcal{G}, \mathcal{S}, \mathcal{M}_{\mathcal{G},\mathcal{S}}\rangle$ and a local model $\mathcal{D}$ for $\mathcal{O}$, we would like to focus our attention on those global interpretations $\mathcal{I}$ that are models of the global ontology $\mathcal{G}$ and that *approximate as much as possible* the satisfaction relation for the mapping $\mathcal{M}_{\mathcal{G},\mathcal{S}}$. One way to formalize this idea is to distinguish between *strict* mappings, as the ones considered in Section 3, and *loose* mappings. In particular, we add to *sound*, *complete*, and *exact* mappings *loosely-sound*, *loosely-complete*, and *loosely-exact* mappings, for which the notion of satisfaction is suitably relaxed, as explained below. Then we define an ordering wrt $\mathcal{D}$ between the models of $\mathcal{G}$. We concentrate directly on the most general case of unrestricted mapping.

If $\mathcal{I}_1$ and $\mathcal{I}_2$ are two models of $\mathcal{G}$, we say that $\mathcal{I}_1$ is better than $\mathcal{I}_2$ wrt $\mathcal{D}$, denoted as $\mathcal{I}_1 \gg_{\mathcal{D}} \mathcal{I}_2$, iff for all triples $\langle V_g, V_s, x\rangle \in \mathcal{M}_{\mathcal{G},\mathcal{S}}$, except for a distinguished one $\langle V_g', V_s', x'\rangle$, where x' is either *loosely-sound*, *loosely-complete*, or *loosely-exact* we have that $V_g^{\mathcal{I}_1} = V_g^{\mathcal{I}_2}$ and $V_s^{\mathcal{I}_1} = V_s^{\mathcal{I}_2} = V_s^{\mathcal{D}}$; while for the distinguished triple $\langle V_g', V_s', x'\rangle$ we have that $V_s'^{\mathcal{I}_1} = V_s'^{\mathcal{I}_2} = V_s^{\mathcal{D}}$ and:

- if $x' = \textit{loosely-sound}$ or $x' = \textit{loosely-exact}$, there exists a tuple $t \in V_s^{\mathcal{D}}$ such that $t \in V_g'^{\mathcal{I}_1}$ and $t \notin V_g'^{\mathcal{I}_2}$;
- if $x' = \textit{loosely-complete}$ or $x' = \textit{loosely-exact}$, there exists a tuple $t \notin V_s^{\mathcal{D}}$ such that $t \notin V_g'^{\mathcal{I}_1}$ and $t \in V_g'^{\mathcal{I}_2}$.

It is easy to verify that the relation $\gg_{\mathcal{D}}$ is a partial order.

With this notion in place we define global models for $\mathcal{O}$ wrt $\mathcal{D}$ those models $\mathcal{I}$ of G that are maximal wrt $\gg_{\mathcal{D}}$, i.e., for no other model $\mathcal{I}'$ of G, $\mathcal{I}' \gg_{\mathcal{D}} \mathcal{I}$.

Example Let us consider an OIS $\mathcal{O}$ consisting of two local ontologies, expressed as the following two $\mathcal{ALCN}$ knowledge bases, $\mathcal{S}_1 = \{R_1(a,b), C_1(b), \ldots\}$ and $\mathcal{S}_2 = \{R_2(a,b), C_2(c), \ldots\}$, a global ontology, also expressed in $\mathcal{ALCN}$, $\mathcal{G} = \{\top \sqsubseteq (\leq 1\, R), \ldots\}$, and the following triples $\langle R, R_1 \sqcup R_2, \textit{loosely-sound}\rangle$, $\langle C, C_1 \sqcup C_2, \textit{loosely-sound}\rangle$, $\cdots$, where the query languages $V_{\mathcal{G}}$ and $\mathcal{V}_{\mathcal{S}}$ are again simply $\mathcal{ALCN}$. Then with the non-monotonic semantics just defined we can verify that a belongs to the answer to the query $\exists R.C$. Observe that, if the mappings were *sound* instead of *loosely-sound*, then $\mathcal{O}$ would be inconsistent, and hence query processing would be compromised.

5 Conclusions

We have discussed the basic notions for an ontology of integration in the semantic web, and we have presented a general framework coherent with such an ontology. The framework represents a sort of design space for the problem of integrating ontologies expressed in DLs within semantic web applications. We have argued that the mapping between the global and the local ontologies is the main aspect of the framework, and we have discussed various approaches for specifying such a mapping. Independently of the approach, we have stressed that the notion of query is crucial for the task of ontology integration. We believe that the problem of applying DLs to the semantic web is strongly related to the possibility of considering queries as first order citizens in DLs, in the spirit of [8], and we hope to see in the future more research efforts by the DL community towards this direction.

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