Adapting Communication Vocabularies using Shared Ontologies

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ABSTRACT

In has been argued that ontologies play a key role in multi-agent communication because they provide and define a shared vocabulary to be used in the course of communication. In real-life scenarios, however, the situation where two agents completely share a vocabulary is rather an exception. More often, each agent uses its own vocabulary specified in a private ontology that is not known by other agents. In this paper we propose a solution to this problem for the situation, where agents share at least parts of their vocabulary. We argue that the assumption of a partially shared vocabulary is valid and sketch an approach for re-formulating terms from the private part of an agent's ontology into a shared part thus enabling other agents to understand them. We further describe how the approach can be implemented using existing technology and proof the correctness of the re-formulation with respect to the semantics of the ontology-language DAML+OIL.

Keywords

Ontologies, Multi-Agent Communication, Approximate Reasoning

1. INTRODUCTION

An important aspect of multi-agent systems is the communication among different agents, because communication is the basis for cooperation. Ontologies are a technology to support inter-agent communication by providing a definition of the world, an agent can ground his beliefs and actions as well as by providing terms that can be used in communication [13]. In practice, agent communication based on ontologies still suffers from many problems. Uschold [19] identifies a number barriers for agent communication that can be separated in language heterogeneity and in terminological heterogeneity. In the following, we will focus on the latter leaving out the problem of heterogeneous languages for encoding knowledge. In fact, agents will often use private ontologies that define terms in different ways making it impossible for the other agent to understand the contents of a message. In these cases there is a need to align ontologies the ontologies used by different agents. Some principled approaches to overcome this problem have been proposed:

- **Emergence:** A very generic approach is to let shared ontologies evolve within the multi-agent systems. Steels uses language games to generate shared ontologies [17]. The approach reported, however, depends on perceptual grounding of agents and assumes an environment that allows for a trial and error phase in communication. In practical applications on the web for example, the situation is different, because legacy ontologies exist and have to be considered.
- **Merging:** In the presence of legacy ontologies, a common approach is to merge existing ontologies resulting in a common one that includes all aspects of the individual ontologies. Stephens and Huhns report an experiment in merging a large number of small ontologies based on matching heuristics [18]. While the result of the experiment is partially convincing, the merging approach is still problematic, because the autonomy of the agents is partially lost by the use of a global ontology.
- **Mapping:** The most often mentioned approach for aligning ontologies on the World Wide Web is the definition of mappings between concepts of different ontologies. Hendler describes this approach that preserves the autonomy of ontological models on a general level [12]. The paper envisions a complex network of ontologies and mappings that enables agents that use different ontologies of the network to communicate via mappings. The use of inter-ontology mappings has been intensively studied in the area of information integration, however, very little work is done on the automatic generation of mappings. As a consequence, the mapping approach requires a lot of manual work and is therefore only pays off for the alignment of ontologies that are frequently used together.

In this paper, we adopt the view of [12] that an intelligent World Wide Web will include a network of different ontologies about various topics that can be used in agent communication. In contrary to Hendler, we do not think that these ontologies will already be linked by mappings, because we expect the effort of establishing these mappings as being too high in many cases. We think that mappings will mostly be established by individual agents that use different available ontologies in order to process a given task. In this view, a connection between the ontologies of different agents is not established by explicit mappings, but rather by existing ontologies that are used by more than one agent. The assumption that agents will share ontologies in our opinion is a necessary requirement for any useful collaboration. Agents will only want to cooperate if they are concerned with a similar domain. While it is not realistic to assume that there will be a single ontology about this domain, it is likely that some core concepts can be standardized and provided as a shared ontology for agents within that domain. There are already efforts going on to standardize fundamental ontologies for domains such a e-Commerce.

In this paper, we propose an approach to facilitate agent communication in the situation, where agents share some but not all of their terminology. In the next section, we describe our approach in an informal way. In section 3 we describe the formal framework our framework is build upon in terms of the ontology language DAML+OIL, its semantics and the formal foundation for inter-ontology mappings. The approach for approximating concepts in a language with a limited vocabulary in described in section 4 and a correctness proof is given. In section 5 we describe how the approximation approach can be used to re-formulate agent messages in such a way that another agent can understand it. We summarize with a discussion and some hints towards future research.

2. COMMUNICATION WITH PARTIALLY SHARED ONTOLOGIES

In order to get a clearer notion of the problem to be solved we make some simplifying assumptions. First of all we will only consider two agents that want to communicate. Then we assume that there are only two ontologies involved, a shared one and a private one of the agent trying to communicate. We further assume that both ontologies are encoded on the same language, preventing us from the problem of integrating the ontology languages. Figure 1 illustrated the situation.

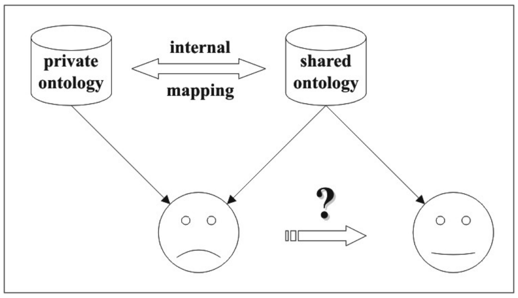

Figure 1: The communication problem

This simplified communication problem can easily be extended to more realistic scenarios as communication is mostly bi-lateral even in complex multi-agent systems. There might be more than two ontologies involved in the communication, but they will all either be shared or private to one on the agents. The only assumption that really is a simplification is the existence of a single ontology language. Investigating this problem, however, is out of the scope of this paper. For an approach to overcome language heterogeneity, we refer to [8] or [16]. In the remainder of this section, we illustrate our approach of translation concepts into a shared terminology. Thereby we only take the sender's point of view and do not consider the relation to the private ontology of the receiving agent.

2.1 Ontology Heterogeneity

In order to perform a task, an agent will use one of more ontologies as an explicit representation of the domain of interest. These ontologies will normally supplement each other to form a sufficiently complete model. Though being supplementary, we can assume that they have sufficient overlap to allow a single agent to find mappings between them. In the following we give a toy example illustrating this idea.

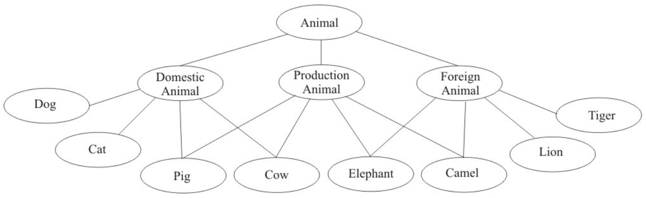

Figure 2: An shared ontology of animals

We use a simple ontology of animals to illustrate the problem (see figure 2). This ontology is shared by the two agents in figure 1. Therefore, the agents can use terms from this ontology (e.g. *Animal*, *Domestic-Animal* or *Cow*) to communicate with each other. A communication problem arises, because the agent on the left hand side of figure 1 also uses a second ontology that contains different classifications of animal like *Pet* or *Farm-Animal*. While the terms from this ontology are closely related to the ones in the shared ontology, the agent on the right-hand side will not be able to understand them.

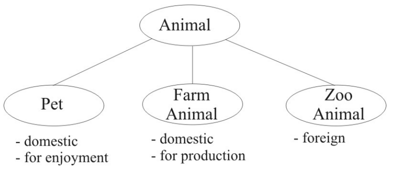

Figure 3: A private ontology of animals

We can assume that each agent using more than one ontology establishes internal mappings between these ontologies. In our example, these mappings would specify *Pet* as being a subclass of *Domestic-Animal* which is disjoint from *Production-Animal*, *Farm-Animal* to be a subclass of *Domestic-Animal* and of *Production-Animal* as well as *Zoo-Animal* to be a subclass of *Foreign-Animal*. In the following, we describe, how these internal mappings can be used in order to facilitate external communication.

2.2 Terminology Adaption

We consider the situation, where the agent wants to find information about the concepts specified in its private ontology (figure 3) In order to be able to communicate this information need to other agents that might have valuable information it has to use terminology from the shared ontology (figure 2).

As an example we take the following query ($Animal \wedge \neg(Farm - Animal)$). This query cannot be directly answered, because the term Farm-Animal is not understood. The idea of our approach is to re-write this query in such a way that it covers the same set of answers using terms from the other ontology. In general, an exact re-writing is not possible because the concepts of the private ontology do not have exactly matching concepts in the shared one. In this case, we have to look for re-writings that approximate the query as closely as possible. Re-writings that are an upper approximation of the original query are know from the database area as *minimal subsuming mappings* [4]. While in the area of databases upper approximations are often used in combination with an additional filter that removes irrelevant results, our approach aims for correctness rather than for completeness and therefore uses a lower approximation.

The idea of the re-writing is the following. Based on the mappings between of the classes in both ontologies, we can find those concepts in the ontology of figure 2 that are most closely related to a query concept. Taking a concepts from our query, we can for example decide that *Domestic-Animal* and *Production-Animal* are upper approximations for *Farm-Animal* while Cow and Pig are lower approximations. Using these concepts, we can define lower boundaries for farm-animals ($Cow \vee Pig$) and use this expression instead of the original concept still getting correct results. In our example, however, the concept occurred in a negated form. In order to return a correct result, we therefore cannot use the lower bound because not all irrelevant resources might be excluded. Based on the considerations made above we can replace the concept farm-animal within the scope of the negation by its upper bound ($Domestic - Animal \wedge Production - Animal$). Using this rewriting, we get the following query that can be shown to return only correct results: ($Animal \wedge \neg(Domestic - Animal \wedge Production - Animal)$).

In the following, we show how the general idea sketched in this section can be implemented on the basis of available reasoning support for ontology languages, i.e. DAML+OIL.

3. REPRESENTATION AND REASONING ABOUT ONTOLOGIES

If we want to guarantee that the re-writing delivers correct results, we need a formal basis for representing and reasoning about the ontologies involved. Recently, the benefits of semantically well-founded ontology languages have been discussed by many authors in connection with the so-called Semantic Web (see e.g. [9]). One of the most important proposals that have been made for well-founded ontology languages for the web is DAML+OIL. In the following, we introduce this language and describe how it can be used to encode and reason about ontologies in order to support our approach.

3.1 The DAML+OIL Language

The DAML+OIL language is a web-based ontology language that has been developed in the DAML programme in order to support intelligent agents to communicate and reason about annotated information on the World Wide Web. Some of the features of the language we can use to precisely define ontological knowledge are the follwing [21].

3.1.1 Class Building Operations

The only possibility to define class structures in RDF schema was the `rdfs:subClassOf` property. DAML+OIL adopts this relation also allowing for multiple inheritance and provides a property for stating that two classes are disjoint.

```
<daml:Class rdf:ID="Domestic-Animal">
    <rdfs:subClassOf rdf:resource="#Animal"/>
</daml:Class>

<daml:Class rdf:ID="Foreign-Animal">
    <rdfs:subClassOf rdf:resource="#Animal"/>
    <daml:disjointWith rdf:resource="#Domestic-Animal"/>
</daml:Class>

<daml:Class rdf:ID="Cow">
    <rdfs:subClassOf rdf:resource="#Domestic-Animal"/>
    <rdfs:subClassOf rdf:resource="#Production-Animal"/>
</daml:Class>
```

The expressiveness of the subclass relation in DAML+OIL is further enriched be the possibility of defining a class to be equivalent to a logical expression over class names.

```
<daml:Class rdf:about="#Animal">
    <daml:disjointUnionOf rdf:parseType="daml:collection">
        <daml:Class rdf:about="#Domestic-Animal"/>
        <daml:Class rdf:about="#Foreign-Animal"/>
    </daml:disjointUnionOf>
</daml:Class>
```

Beside the `daml:disjointUnionOf` property, classes can also be defined to be equivalent to another class, to equivalent to a Boolean expression over classes using `daml:intersectionOf`, `daml:unionOf` and `daml:complementOf` or by enumerating its elements with the `daml:oneOf` property.

3.1.2 Relations

DAML+OIL defines two kinds of relations. `daml:ObjectProperty` relates members of different classes to each other. `daml:DatatypeProperty` relates a member of a class to a legal value of a certain data type. The first type of relation is very similar to an RDF property. It has a unique name and can have RDF schema range and domain restrictions like the following example:

```
<daml:ObjectProperty rdf:ID="has-origin">
    <rdfs:domain rdf:resource="#Animal"/>
    <rdfs:range rdf:resource="#Country"/>
</daml:ObjectProperty>
```

The first enhancement to RDF schema employed by DAML+OIL is the possibility of defining one relation to be the equivalent or the inverse of another relation. Using this feature, we can define the `has-child` relation using the one specified above:

```
<daml:ObjectProperty rdf:ID="is-origin-of">
    <daml:inverseOf rdf:resource="#has-origin"/>
</daml:ObjectProperty>
```

Just as RDF schema, hierarchies of relations can be specified using the `rdfs:subpropertyOf` operator. Further, special properties can be assigned to relations, for details we refer to [21].

3.1.3 Property Restrictions

Classes define common properties of its members. Different from RDF schema, DAML+OIL provides means for defining these characteristic properties of class members in terms of restrictions on the objects they are related to. In principle there are two kinds of restrictions, type restrictions and number restrictions:

```
<daml:Class rdf:ID="Person">
    <rdfs:subClassOf rdf:resource="#Animal"/>
    <rdfs:subClassOf>
        <daml:Restriction daml:cardinalityQ="1">
            <daml:onProperty rdf:resource="#has-origin"/>
            <daml:hasClassQ rdf:resource=#Country/>
        </daml:Restriction>
    </rdfs:subClassOf>
</daml:Class>
```

The restriction `daml:toClass` from the example claims that every object related to a member of the class has be be of a certain type. Beside this restriction, `daml:hasClass` claims that every member of the class is related to one object of a certain type, `daml:hasValue` even claims that every object of the class is related to one specific object. Number restrictions `daml:minCardinality`, `daml:maxCardinality` and `daml:cardinality` define lower and upper boundaries and exact values for the number of objects the member of a class is related to via a certain relation. Several restrictions may apply to a relation.

3.2 Semantics of DAML+OIL

In [20] a formal semantics for DAML+OIL is described. The semantics is based on an interpretation mapping into an abstract domain. More specifically, every concept name is mapped on a set of objects, every property name is mapped on a set of pairs of objects. Individuals (in or case resources) are mapped on individual objects in the abstract domain. Formally, an interpretation is defined as follows:

Definition 1 (Interpretation). *An Interpretation consists of a pair* $(\Delta, .^{\mathcal{E}})$ *where* Δ *is a (possibly infinite) set and* $.^{\mathcal{E}}$ *is a mapping such that:*

- $x^{\mathcal{E}} \in \Delta$ *for all individual names* x.
- $C^{\mathcal{E}} \subseteq \Delta$ *for all concept names* C
- $R^{\mathcal{E}} \subseteq \Delta \times \Delta$ *for all role names* R

We call $.^{\mathcal{E}}$ *the extension of a concept, a role, or an individual, respectively.*

This notion of an interpretation is a very general one and does not restrict the set of objects in the extension of a concept. This is done by the use of operators for defining classes. In our example, we used the `subClassOf` and the `hasValue` operator for restricting the set of objects that are members of the class zoo animals. These kinds of operators restrict the possible extensions of a concept. Figure 4 summarizes the specific interpretations of a part of the operators of DAML+OIL.

Operator	**Extension** $.^{\mathcal{E}}$
`intersectionOf`	$C_1^{\mathcal{E}} \cap \cdots \cap C_n^{\mathcal{E}}$
`unionOf`	$C_1^{\mathcal{E}} \cup \cdots \cup C_n^{\mathcal{E}}$
`complementOf`	$\Delta - C^{\mathcal{E}}$
`oneOf`	$\{x_1, \cdots, x_n\} \subset \Delta$
`toClass`	$\{y \in \Delta \| (y,x) \in P^{\mathcal{E}} \implies x \in C^{\mathcal{E}}\}$
`hasClass`	$\{y \in \Delta \| \exists x((y,x) \in P^{\mathcal{E}}) \wedge x \in C^{\mathcal{E}}\}$
`hasValue`	$\{y \in \Delta \| (y,x) \in P^{\mathcal{E}}\}$
`minCardinalityQ`	$\{y \in \Delta \| \ \|\{x \| (y,x) \in P^{\mathcal{E}} \wedge x \in C^{\mathcal{E}}\}\| \leq n\}$
`maxCardinalityQ`	$\{y \in \Delta \| \ \|\{x \| (y,x) \in P^{\mathcal{E}} \wedge x \in C^{\mathcal{E}}\}\| \geq n\}$
`cardinalityQ`	$\{y \in \Delta \| \ \|\{x \| (y,x) \in P^{\mathcal{E}} \wedge x \in C^{\mathcal{E}}\}\| = n\}$

Figure 4: Terminological Operators of DAML+OIL

These kinds of restriction are the basis for deciding whether a class definition is equivalent, more specialized or more general than another. Formally, we can decide whether one of the following relations between two expressions hold:

subsumption: $C_1 \sqsubseteq C_2 \iff C_1^{\mathcal{E}} \subseteq C_2^{\mathcal{E}}$

membership: $x : C \iff x^{\mathcal{E}} \in C^{\mathcal{E}}$

In order to implement information filtering, we need subsumption in order to determine the upper and lower boundaries of a concept. Membership is used in order to retrieve relevant resources that match a query.

3.3 Inter-Ontology Mappings

For a long time, representation and reasoning in description logics, which provide the semantic basis for DAML+OIL, has only been investigated in terms of a single homogeneous model. Recently Borgida and Serafini proposed an extension of the formal framework of description logics to distributed knowledge models [3]. The extended framework consists of a set of terminological knowledge bases (ontologies) T_i and a set of so-called bridge rules between concept definitions from different ontologies. Two kinds of bridge rules are considered (the prefixes indicate the ontology a concept definition is taken from):

into rule $i : C \xrightarrow{\sqsubseteq} j : D$

onto rule $i : C \xrightarrow{\sqsupseteq} j : D$

The interpretation of the first rules is that the instances of the concept C in ontology T_i are mapped to a subset of the instances of the concept D in ontology T_j $(i : C^{\mathcal{E}} \subseteq j : D^{\mathcal{E}})$ in the case of the second rule the superset relation is asserted to hold between the instances of the two concepts. Using the formal framework of Borgida and Serafini, we can define the internal mappings between private and shared ontologies informally defined above.

$$Zoo - Animal \xrightarrow{\sqsubseteq} \neg Domestic - Animal \quad (1)$$

$$Pet \xrightarrow{\sqsubseteq} Domestic - Animal \wedge \neg Production - Animal \quad (2)$$

$$Farm - Animal \xrightarrow{\sqsubseteq} Domestic - Animal \wedge Production - Animal \quad (3)$$

Another important result reported in [3] is the ability to transform a distributed knowledge base into a global one and apply existing description logic reasoner in order to derive new knowledge. In the following, we build on this result whenever we mention terminological reasoning.

4. APPROXIMATING CONCEPTS

The classes in a DAML+OIL ontology form a hierarchy with respect to the subsumption relation. In a distributed Description Logic, such a hierarchy can also be computed for separate ontologies that are connected by bridge rules. Therefore, we will always have a set of direct super- and a set of direct subclasses of a class c_1 from the private ontology. We can use those direct sub- and superclasses that belong to the shared ontology as upper and lower approximation for c_1 in the shared ontology:

Definition 2 (Lower Approximation). *Let C_1 be a set of private concepts, C_2 a set of shared concepts of an agent and $c \in C_1$ a class, then a class $c_{glb} \in C_2$ is called a lower approximation of c in IS_2, if the following assertions hold:*

1. $c_{glb} \sqsubseteq c$
2. $(\exists c' \in C_2 : c' \sqsubseteq c) \implies (c' \sqsubseteq c_{glb})$

The greatest lower bound $glb_{IS_2}(c)$ denotes the set of all lower approximations of c in C_2.

Definition 3 (Upper Approximation). *Let C_1 be a private classes , C_2 a set of shared classes of an agent and $c \in C_1$ a private class, then a class $c_{lub} \in C_2$ is called an upper approximation of c in IS_2, if the following assertions hold:*

1. $c \sqsubseteq c_{lub}$
2. $(\exists c' \in C_2 : c \sqsubseteq c') \implies (c_{lub} \sqsubseteq c')$

The least upper bound of $lub_{IS_2}(c)$ is the set of all least upper bounds of c in C_2.

The rational of using these approximations is that we can decide whether an entity x is a member of a class in the private ontology based on its membership in classes of the shared ontology. This decision in turn provides us with an approximate result on deciding whether x is the result of a query stated in terms of a private ontology, based on the following observation:

- If x is member of a lower bound of c_1 then it is also in c_1
- If x is not member of all upper bounds of c_1 then it is not in c_1

In [15] Selman and Kautz propose to use this observation about upper and lower boundaries for theory approximation. We adapt the proposal for defining an approximate classifier M' that assigns members of shared concepts to private ones in the following way:

Definition 4 (Concept Approximation). *Let C_1 be a set of private concepts, C_2 a set of shared concepts of an agent and x the member of a shared concepts then for every $c_1 \in C_1$ we define M' such that:*

- $M'(x, c_1) = 1$ *if* $x : \left(\bigvee_{c \in glb_{IS_2}(c_1)} c \right)$
- $M'(x, c_1) = 0$ *if* $x : \neg \left(\bigwedge_{c \in lub_{IS_2}(c_1)} c \right)$
- $M'(x, c_1) = ?$*, otherwise*

Where the semantics of disjuction and conjunction is defined in the obvious way using set union and intersection .

Based on the observation about the upper and lower bounds, we can make the following assertion about the correctness of the proposed approximate classification:

Proposition 1 (Correctness of Approximation). *The approximation from definition 4 is correct in the sense that:*

1. *If* $M'(x, c_1) = 1$ *then* $x^{\mathcal{E}} \in c_1^{\mathcal{E}}$
2. *If* $M'(x, c_1) = 0$ *then* $x^{\mathcal{E}} \notin c_1^{\mathcal{E}}$

Using the definition of upper and lower bounds the correctness of the classification can be proven in a straightforward way:

Proof. (1) If the classification returns $M'(x, c_1) = 1$ then $x : (\bigvee_{c \in glb_{IS_2}(c_1)} c)$. Using definition 2 we get that for all c we have $c \sqsubseteq c_1$ and therefore also $(\bigvee_{c \in glb_{IS_2}(c_1)} c) \sqsubseteq c_1$ (by set theory). Using the definition of subsumption we can conclude that $x^{\mathcal{E}} \in c_1^{\mathcal{E}}$.

(2) Using definition 3 we deduce that for all c we have $c_1 \sqsubseteq c$ and therefore $c_1 \sqsubseteq \bigwedge_{c \in lub_{IS_2}(c_1)} c$. This means that $x^{\mathcal{E}} \in c_1^{\mathcal{E}}$ only if $x^{\mathcal{E}} \in (\bigwedge_{c \in lub_{IS_2}(c_1)} c)^{\mathcal{E}}$. However if the classification returns $M'(x, c_1) = 0$ then $x : \neg(\bigwedge_{c \in lub_{IS_2}(c_1)} c)$ which is equivalent to $x^{\mathcal{E}} \notin (\bigwedge_{c \in lub_{IS_2}(c_1)} c)^{\mathcal{E}}$. Therefore we also have $x^{\mathcal{E}} \notin c_1^{\mathcal{E}}$. □

5. ADAPTING THE COMMUNICATION LANGUAGE

The considerations from last section provide a formal basis for re-writing concepts using in messages an agent uses to communicate with other agents. Having proven the correctness of the approximation we can use them to re-write a concepts by replacing their names by their approximation.

Definition 5 (Concept Re-Writing). *The rewriting of a query c over concepts from a private ontology to an expression over concepts from a shared ontology is defined as as follows:*

- *replace every non negated concept name c by:* $\bigwedge_{c' \in lub_{IS_2}(c)} c'$

- *replace every negated concept name c by:* $\bigvee_{c' \in glb_{IS_2}(c)} c'$

The rewriting a concept can easily be implemented using any available Description logic reasoner. We used the Description Logic System RACER [11]. We can compute the re-writing using Algorithm 1. The input for the algorithm is the message to be re-written, the names of shared concepts as well as a model of both ontologies.

Algorithm 1 Translate-Message

Require: The Message to be translated: C
Require: A list of shared concepts: S
Require: A terminological knowledge base T
  racer.in-tbox(T)
  for all t is an concept term in C **do**
    if t is negated **then**
      $B[t]$:= racer.directSupers(t)
      $B'[t] := B[t] \cap S$
      $Q(t) := (c_1 \wedge \cdots \wedge c_n)$ for $c_i \in B'[t]$
    else
      $B[t]$:= racer.directSubs(t)
      $B'[t] := B[t] \cap S$
      $C(t) := (c_1 \vee \cdots \vee c_n)$ for $c_i \in B'[t]$
    end if
    C' := **proc** Replace t in C' by $C(t)$
  end for
  return C'

As the re-writing builds upon the approximations discussed in the last section we can guarantee that the result of the query is correct. Moreover, we can use subsumption reasoning in order to determine this result. To be more specifically, a resource x is indeed a member of the query concept if membership can be proved for the re-written query.

Example Translation: We illustrate how the Algorithm works using an example translation. We assume that the message contains the request for information:

> 'Give me information about *Farm-Animals* and *Animals* that are not *Pets*.'

Besides this message the algorithm will be provided with a list of shared concepts. In this case these concepts are all concepts from figure 2. Further, the algorithm will need the DAML+OIL definitions of the classes involved as well as specifications of the mappings. These together form the terminological knowledge base mentioned in the algorithm.

In the first step, the algorithm will extract all concept terms from the message that are defined in the terminological knowledge base. In our case these are the terms *Farm-Animal*, *Animal* and *Pet*. As *Animal* is contained in the shared ontology it does not have to be translated. We therefore only discuss the translation of *Farm-Animal* and *Pet*.

In the second step, the algorithm tests whether the concepts are negated or not. As *Farm-Animal*is not negated, the algorithm collects all direct subclasses of *Farms-Animal* from the knowledge base. These are *Cow* and *Pig* (compare equation 3 and figure 2). These are connected by disjunction to form the lower bound ($Cow \vee Pig$). Next, the negated term *Pet* is handled. The algorithm computes the direct superclasses *Domestic-Animal* (compare equation 2 and figure 2) which is also the upper bound.

In the last step, the algorithm replaces the concepts in the message by the corresponding bounds that have been computed. The resulting message is the following:

> 'Give me information about *Cows or Pigs* and *Animals* that are not *Domestic Animals*.'

As this message only contains terms from the shared ontology, it is understood and can be processed by the receiving agent.

6. RELATED WORK

The idea of rewriting representations based on the special capabilities of a remote system is first reported in [14]. It has been applied in the area of information retrieval [5] to translate full-text queries and in database systems for translating SQL queries [4]. The use of description logics for query rewriting is described in [10]. Baader and others propose a general framework for rewriting concepts [1]. This work is closest to our approach, however, our goal is not to achieve equivalent rewritings, but rather use an approximation approach that is more handable in practice.

7. CONCLUSIONS

We described an approach for exploiting partially shared ontologies in multi-agent communication by translating private concepts into shared ones while ensuring some formal properties. Our approach enables agents on the World Wide Web to exchange semantic information solely relying on internally provided mappings between ontologies. So far, we consider our results as a basic mechanism for facilitating agent communication. However, a lot of work is still necessary in order to apply it in practice. We only want to mention two specific aspects that have to be addressed in this context: First of all, sophisticated communication protocols have to be developed that agents can use in order to find out, which are the ontologies they share and what are the options for re-writing. First investigations in ontology negotiation are reported in [2]. Further [7] suggest to use more complex object and concept definitions in agent messages. Rewriting such complex definitions instead of just concept names requires more sophisticated mechanisms.

Further steps in the direction of this research will be taken in the context of intelligent peer-to-peer networks which are the main topic of the IST project SWAP (Semantic Web and Peer-to-Peer). We will investigate how the approach behaves at a larger scale using two case studies. These case studies will provide us with a better understanding of the validity of the assumptions we made about the existence of shared ontologies and the integration of ontologies within a single agent. Further, a larger network of agents will enable us to investigate the use of third parties for mediating between agents that only share ontologies with this third party, resulting in a more complex scenario.

8. REFERENCES

[1] F. Baader, R. Kuesters, and R. Molitor. Rewriting concepts using terminologies. In T. Cohn, F. Giunchiglia, and B. Selman, editors, *Proceedings of the seventh International Conference on Principles of Knowledge Representation and Reasoning KR'2000*. Morgan Kaufmann, 2000.

[2] S. Bailin and W. Truszkowski. Ontology negotiation between agents supporting intelligent information management. In *OAS'01 Ontologies* [6].

[3] A. Borgida and L. Serafini. Distributed description logics. In *Proceedings of the Internaltional Description Logics Workshop DL'2002*, 2002.

[4] K.-C. Chang and H. Garcia-Molina. Approximate query mapping: Accounting for translation closeness. *The VLDB Journal*, 10:155–181, 2001.

[5] K.-C. Chang, H. Garcia-Molina, and A. Paepcke. Boolean query mapping across heterogeneous information sources. *IEEE Transaction on Knowledge and Data Engineering*, 8(4), 1996.

[6] S. Cranefield, T. Finin, and S. Willmott. Oas'01 ontologies and agent systems. CEUR Workshop Proceedings 52, RWTH Aachen, 2001.

[7] S. Cranefield and M. Purvis. Generating ontology-specific content languages. In *OAS'01 Ontologies in Agent Systems* [6].

[8] J. Euzenat. An infrastructure for formally ensuring interoperability in a heterogeneous semantic web. In I. F. Cruz, S. Decker, J. Euzenat, and D. McGuinness, editors, *Proceedings of the First Semantic Web Working Symposium*, Stanford, CA, USA, 2001.

[9] D. Fensel, I. Horrocks, F. van Harmelen, D. L. McGuinness, and P. F. Patel-Schneider. Oil: An ontology infrastructure for the semantic web. *IEEE Intelligent Systems*, 16(2), 2001.

[10] F. Goasdoue and M.-C. Rousset. Rewriting conjunctive queries using views in description logics. 2000.

[11] V. Haarslev and R. Moller. Description of the RACER system and its applications. In *Proceedings of the Description Logics Worlshop DL-2001*, Stanford, CA, 2001.

[12] J. Hendler. Agents and the semantic web. *IEEE Intelligent Systems*, pages 30–37, March/April 2001.

[13] M. Huhns and M. Singh. Ontologies for agents. *IEEE Internet Computing*, pages 81–83, November/December 1997.

[14] Y. Papakonstantinou, A. Gupta, and L. Haas. Capabilities-based query rewriting in mediator systems. In *Proceedings of 4th International Conference on Parallel and Distributed Information Systems*, Miami Beach, Flor., 1996.

[15] B. Selman and H. Kautz. Knowledge compilation and theory approximation. *Journal of the ACM*, 43(2):193–224, March 1996.

[16] M. Sintek and S. Decker. TRIPLE - a query, inference and transformation language for the semantic web. In *Proceedings of the First International Semantic Web Conference (ISWC)*, Sardinia, 2002.

[17] L. Steels. The origins of ontologies and communication conventions in multi-agent systems. *Autonomous Agents and Multi-Agent Systems*, 1(1):169–194, October 1998.

[18] L. Stephens and M. Huhns. Consensus ontologies - reconciling the semantics of web pages and agents. *IEEE Internet Computing*, pages 92–95, September/October 2001.

[19] M. Uschold. Barriers to effective agent communication. In *OAS'01 Ontologies in Agent Systems* [6].

[20] F. van Harmelen, P. F. Patel-Schneider, and I. Horrocks. A model-theoretic semantics for daml+oil (march 2001). http://www.daml.org/2001/03/model-theoretic-semantics.html, march 2001.

[21] F. van Harmelen, P. F. Patel-Schneider, and I. Horrocks. Reference description of the daml+oil (march 2001) ontology markup language. http://www.daml.org/2001/03/reference.html, march 2001.