Toward Multi-Viewpoint Reasoning with OWL Ontologies

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Abstract. Despite of their advertisement as task independent representations, the reuse of ontologies in different contexts is difficult. An explanation for this is that when developing an ontology, a choice is made with respect to what aspects of the world are relevant. In this paper we deal with the problem of reusing ontologies in a context where only parts of the originally encoded aspects are relevant. We propose the notion of a viewpoint on an ontology in terms of a subset of the complete representation vocabulary that is relevant in a certain context. We present an approach of implementing different viewpoints in terms of an approximate subsumption operator that only cares about a subset of the vocabulary. We discuss the formal properties of subsumption with respect to a subset of the vocabulary and show how these properties can be used to efficiently compute different viewpoints on the basis of maximal sub-vocabularies that support subsumption between concept pairs.

1 Introduction

Originally, ontologies where meant as a task-neutral description of a certain domain of interest that can be reused for different purposes. This idea is also at the heart of the semantic web vision, where the ontology-based description of Information is supposed to make it possible to use the information for different purposes and in different contexts. In practice, however, it has turned out that the re-use of ontologies for different tasks and purposes causes problems [15]. The reason for this is that ontologies are often not really designed independent of the task at hand. The development is rather driven by the special needs of a particular system or task. In general the context of use has an impact on the way concepts are defined to support certain functionalities. As some aspects of a domain that are important for one application do not matter for another one and vice versa, an ontology does not represent the features needed for a particular application. In this case, there is little hope for direct reuse. Another potential problem, that we will address in this paper is that an ontology contains too many aspects of a domain. This can become a problem, because in introduces unnecessary complexity and can even lead to unwanted conclusions, because the ontology introduces unwanted distinctions between classes that should be treated in the same way in the current application context. We argue that in order to solve this problem, we have to find ways to enable the representation of different viewpoints on the same ontology, that better reflects the actual needs of the application at hand.

1.1 Related Work

The concept if having different viewpoints on the same model is a well established concept in the area of software engineering [8]. In order to extend this to semantic web systems, the concept of a viewpoint has to be extended to the semantic models used in the system. There has been some work on specifying viewpoints on RDF data, mainly inspired by the concept of views in database systems. The idea is to define rules for extracting an possibly restructuring parts of a basic RDF model to better reflect the needs of a certain user or application. Different techniques have been proposed including the use of named queries [10], the definition of a view in terms of graph traversal operations [11] and the use of integrity constraints for ensuring the consistency of a viewpoint [16]. In this paper, we focus on ontologies represented in description logics, in particular OWL-DL. In the context of description logics, the classical notion of views can only be used in a restricted way as relevant inference problems related to views have been shown to be undecidable [3].

An alternative approach to viewpoints in description logics has been proposed based on the concept of contextual reasoning . Here, each viewpoint is represented in terms of a separate model with a local interpretation [9]. Relations between different viewpoints are represented by context mappings that constrain the local interpretations. Based on these basic principles of contextual reasoning, approaches for representing and linking different viewpoints on the same domain have been developed for description logics [4] and for OWL resulting the C-OWL language [6]. These approaches, however have a slightly different goal as they mainly aim at providing means for integrating different existing models. Our interest is to develop methods that allows us to extract a certain viewpoint from an existing model that best fits the requirements of an application.

An approach that is very similar to this idea is the work of Arara and others [12, 1]. They propose the use of modal description logics for encoding multiple viewpoints in the same ontology by indexing parts of the definitions with the contexts they are supposed to hold in. A drawback of their approach is that they require an extension of the representation language and its semantics to deal with multiple perspectives. In contrast to the contextual approaches mentioned above there currently is no reasoning support for this formalism.

1.2 Contributions and Motivating Example

In this paper, we propose an approach for multi-viewpoint reasoning that do not require an extension to the OWL-DL language. The approach is based on the idea of approximate logical reasoning and uses an approximate subsumption operator that can be tuned to only use a certain part of the definitions in the ontology. In particular, we address the problem of efficient computing concept hierarchies that represent a certain viewpoint on a domain in terms of ignoring a certain subset of the vocabulary used in concept expressions.

To clarify this idea we consider the family ontology shown in figure 1. The ontology classifies persons into different concepts according to certain criteria including gender and the presence of children.

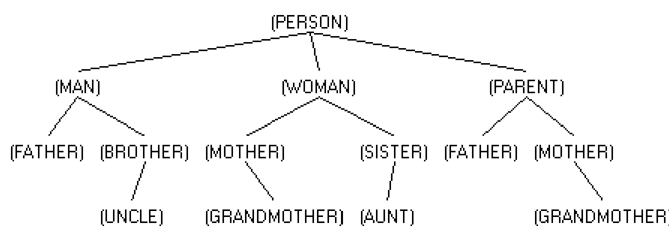

Fig. 1. The Example Ontology

The silent assumption underlying this ontology is that all of the criteria used in the definitions are actually relevant for the application. In particular, the assumption is that it is important to distinguish between male and female persons (man vs. woman) and between people with and without children (woman vs. mother).

We can imagine applications that would benefit from an ontology of people, but in which only some of the distinguishing aspects are important. An example would be a system for processing salary information in the German public sector. In such a system it makes sense to distinguish between people with and without children, because the existence of children entitles to special benefits. The distinction between genders in completely irrelevant in this context and even prohibited by laws guaranteeing gender equality. Other applications e.g. related to private pension funds the gender is relevant as there are different regulations with respect to the age in which male and female persons can retire. In this application the existence of children is not important.

The paper is structured as follows. In section 2 first briefly introduce Description Logics as a basis for representing ontologies including some modeling examples from our example ontology and review the notion of approximate deduction in description logics proposed by Cadoli and Schaerf [13]. Section 3 introduces our notion of a viewpoint and its definition in terms of an approximate subsumption operator. In section 4 we discuss some axiomatic properties of the approximate subsumption operators and discuss their use for implementing basic reasoning services relevant for multi-viewpoint reasoning. The paper concludes with a discussion of the approach.

2 The Description Logics $\mathcal{SIN}$

The basic modeling elements in Description Logics are concepts (classes of objects), roles (binary relations between objects) and individuals (named objects). Based on these modeling elements, Description Logics contain operators for specifying so-called concept expressions that can be used to specify necessary and sufficient conditions for membership in the concept they describe. Basic reasoning tasks associated with these kinds of logics are checking whether an expression is satisfiable (whether it is possible that an object satisfies the membership condition) and deciding subsumption between two concepts (deciding whether a concept expression implies another one). We now look at these issues on a more formal level.

Let $\mathcal{C}$ be a set of concept names and R a set of role names. Further let there be a set $R^+ \subseteq R$ of transitive roles (i.e. for each $r \in R^+$ we have $r(x,y) \wedge r(y,z) \Rightarrow r(x,z)$). If now R^- denotes the inverse of a role (i.e. $r(x,y) \Rightarrow r^-(y,x)$) then we define the set of roles as $R \cup \{r^- | r \in R\}$. A role is called a simple role if it is not transitive. The set of concepts (or concept expressions) in $\mathcal{SIN}$ is the smallest set such that:

- $\top$ and $\bot$ are concept expressions
- every concept name A is a concept expression
- if C and D are concept expressions, r is a role, s is a simple role and n is a non-negative integer, then $\neg C$, $C \sqcap D$, $C \sqcup D$,$\forall r.C$, $\exists r.C$, $\geq n\, r$ and $\leq n\, r$ are concept expressions.

A general concept inclusion axioms is an expression $C \sqsubseteq D$ where C and D are concepts, the equivalence axiom $C \equiv D$ is defined as $C \sqsubseteq D \wedge D \sqsubseteq C$ A terminology is a set of general concept inclusion and role inclusion axioms. In the following, we only consider axioms of the form $A \sqsubseteq C$ and $A \equiv C$ where A is an atomic concept name. Further, we assume that all concepts C are in negation normal form (negation only applies to atomic concept names). Note that for every concept can deterministically be transformed into an equivalent concept in negation normal form. Thus this assumption does not impose any restriction on the approach.

This logic covers a significant part of the OWL-DL Language. We exclude the following language elements, because their behavior in connection with the approximation approach presented below needs more investigation:

– Role Hierarchies: It is not clear how to deal with the situation where we want to consider a certain role but not its super-roles.
– Qualified Number restrictions: The use of qualified number restrictions make it hard to predict the effect of restricting reasoning to a sub-vocabulary, because ignoring the type restriction to C in the expression $(\geq n\, r.C)$ makes the overall expression more general whereas ignoring C in $(\leq n\, r.C)$ makes the expression more specific.
– Nominals: The current mechanism for implementing multi-viewpoint reasoning is based on concept and role names and does not cover objects as part of the signature of an ontology.
– General Concept Inclusion Axioms: The presence of general inclusion axioms makes it hard to determine the impact of ignoring parts of the vocabulary on the interpretation of a certain concept.

Examples In the following we illustrate the use of description logic for defining and reasoning about concepts in our example ontology from figure 1. In particular, we look at the definitions of concepts related to motherhood. In our ontology the concept mother is defined as an intersection of the concepts Woman and Parent stating that each mothers is both, a woman and a parent.

$$\texttt{Mother} \equiv \texttt{Woman} \sqcap \texttt{Parent}$$

These two concepts in turn are defined as special cases of the person concept using the relations `has-gender` and `has-child`. In particular, these relations are used to claim that each woman must have the gender female and that each parent must have a person as a child.

$$\texttt{Woman} \equiv \texttt{Person} \sqcap \exists \texttt{has} - \texttt{gender.Female}$$

$$\texttt{Parent} \equiv \texttt{Person} \sqcap \exists \texttt{has} - \texttt{child.Person}$$

Finally, the concept of a grandmother is defined by chaining the has-child relation to state that every instance of this class is a Woman with a child that has a child itself which is a Person.

$$\texttt{Grandmother} \equiv \texttt{Woman} \sqcap \exists \texttt{has} - \texttt{child.}(\exists \texttt{has} - \texttt{child.Person})$$

Description Logics are equivalent to a fragment of first order logic. Corresponding semantics preserving translation rules from Description logic expressions are given in [2, 5, 14]. Subsumption between concepts $(C \sqsubseteq D)$ can be decided based on this semantics. In particular one concept subsumes another if the first order representation of D is implied by the first order representation of C. This way, we can for example find out that `Grandmother` is a subclass of `Mother`.

3 Reasoning with Limited Vocabularies

The idea of reasoning with limited vocabularies has been used in the area of approximate reasoning in order to improve efficiency of propositional inference. Cadoli and Schaerf propose a notion of approximate entailment that allows errors on parts of the vocabulary – in their case propositional letters [13]. We adopt the general idea of allowing errors on parts of the vocabulary and generalize this idea to the case where the vocabulary does not consist of propositional letters, but of concepts and relations. Cadoli and Schaerf also present an extension of their approach to description logics, but in this work the sub-vocabulary does not correspond to concept and role names but rather to the position of a subexpression [7]. As our aim is to provide a mechanism for "switching on and off" certain concept and relation names, we have to find a different way of defining inference with respect to a certain sub-vocabulary.

3.1 Vocabulary-Limited Subsumption

The basic idea of our approach to inference with limited vocabularies is that terminologies define restrictions on the interpretation of certain concepts. Based on these restrictions, we can decide whether one concept is subsumed by another one. In the case of a limited vocabulary, we only want to consider such restrictions that relate to a certain sub-vocabulary under consideration and ignore other restriction. If we want to implement this idea, the basic problem is to identify and eliminate those restrictions that are not related to the sub-vocabulary under consideration. Here we have to distinguish two kinds of restrictions:

1. the interpretation of a concept can be restricted by claiming that instances of this concept belong to a set defined by a Boolean expression over other concept names.
2. the interpretation of a concept can be restricted by claiming that instances of the concept are related to other object with certain properties via a certain relation.

We can deal with the first kind of restriction in the same way as with propositional logic. Therefore we adopt the approach of Cadoli an Schaerf who replace concepts that are not in the relevant sub-vocabulary as well as their negations by true. For the case of Description logics this means that we replace concepts and their negations by $\top$, thus disabling the restriction imposed by them.

The second kind of restrictions can be dealt with by just ignoring those restrictions that are related to a certain relation. This includes the restrictions on the related objects. More specifically, we can disable these kind of restrictions by replacing subexpressions that contain a relations $r \notin V$ – in particular subexpressions of the form $(\exists r.C), (\forall r.C), (\geq n\, r)$ and $(\leq n\, r)$ – by $\top$.

Definition 1 (Approximation). *Let $\mathcal{V} = \mathcal{C} \cup \mathcal{R}$ be the vocabulary (the set of all concept and role names) of an ontology. Let further $V \subseteq \mathcal{V}$ be a subset of $\mathcal{V}$ and X a concept expression in negation normal form, then the approximation of a concept expression X $approx_V(X)$ is defined by:*

– *Replacing every concept name $c \in \mathcal{V} - V$ that occurs in X and its negation by $\top$*
– *Replacing every subexpression of X that directly contains a slot name $r \in \mathcal{V} - V$ and its negation by $\top$*

The restriction of terminologies to axioms that only have atomic concept names on the left hand side allows us to apply the approximation defined above to complete terminologies in a straightforward way by replacing the right hand sides of the axioms in a terminology by their approximation. Further, we remove the definitions of concepts not in V as they are irrelevant. the corresponding definition of an approximated terminology is the following:

Definition 2 (Approximated Terminology). *Then we define the approximation of a terminology $\mathcal{T}$ with respect to sub-vocabulary V as*

$$\mathcal{T}_V = \{A \sqsubseteq approx_V(C) | A \in V, (A \sqsubseteq C) \in \mathcal{T}\} \cup \{A \equiv approx_V(C) | A \in V, (A \equiv C) \in \mathcal{T}\}$$

The approximated terminology T_V represents the original model while ignoring the influence of the concepts and relations not in V. Consequently, if we can derive a subsumption statement $C \sqsubseteq D$ from this terminology, we can interpret this as subsumption with respect to the sub-vocabulary V.

Definition 3 (Subsumption wrt a sub-vocabulary). *Let $\mathcal{T}$ be a terminology with sub-vocabulary $V \subseteq \mathcal{V}$, let further $C, D \in V$ be concept names in V, then we define the notion of subsumption with respect to sub-vocabulary V as:*

$$\mathcal{T} \models C \underset{V}{\sqsubseteq} D \Leftrightarrow_{def} \mathcal{T}_V \models C \sqsubseteq D$$

In this case, we say that C is subsumed by another concept D with respect to sub-vocabulary V

The definition leaves us with a family of subsumption operators, one for each subset of the vocabulary. Below we illustrate the use of the operator with respect to the motivating example.

Example 1: Gender We can now apply the notion of subsumption with respect to a sub-vocabulary to our example ontology and exclude certain aspects from the definitions. The first is the case where the target application does not care about the gender of a person. We treat this case by replacing the classical notion of subsumption by subsumption with respect to the vocabulary $\mathcal{V} - \{\texttt{has} - \texttt{gender}\}$. We implement this by replacing subexpressions that directly contain the slot has-gender by $\top$. The result of this operation on the example definitions from above are:

$$\texttt{Woman} \equiv \texttt{Person} \sqcap \top$$

$$\texttt{Parent} \equiv \texttt{Person} \sqcap \exists \texttt{has} - \texttt{child}.\texttt{Person}$$

$$\texttt{Mother} \equiv \top \sqcap \texttt{Parent}$$

$$\texttt{Grandmother} \equiv \texttt{Mother} \sqcap \exists \texttt{has} - \texttt{child}.(\exists \texttt{has} - \texttt{child}.\texttt{Person})$$

As a consequence of this operation, there are a number of changes in the inferable concept hierarchy. In particular, the concept `Mother` becomes equivalent to `Person` with respect to the sub-vocabulary $\mathcal{V} - \{\texttt{has} - \texttt{gender}\}$. The same happens with respect to the concept `Man` which also becomes equivalent to the other two concepts with respect to $\mathcal{V} - \{\texttt{has} - \texttt{gender}\}$. This means that the ontology does not make a distinction between male and female persons any more which is exactly what we wanted to achieve.

Example 2: Children In the same way, we can implement our second motivating example where we do not want to distinguish between persons with and without children. For this case, we use subsumption with respect to sub-vocabulary $\mathcal{V} - \{\texttt{has} - \texttt{child}\}$. Replacing the corresponding subexpressions in our example by $\top$ leads to the following definitions:

$$\texttt{Woman} \equiv \texttt{Person} \sqcap \exists \texttt{has} - \texttt{gender}.\texttt{Female}$$

$$\texttt{Parent} \equiv \texttt{Person} \sqcap \top$$

$$\texttt{Mother} \equiv \texttt{Woman} \sqcap \texttt{Parent}$$

$$\texttt{Grandmother} \equiv \texttt{Mother} \sqcap \top$$

In this case, we see that the concept `Parent` becomes equivalent to `Person` with respect to subvocabulary $\mathcal{V} - \{\texttt{has} - \texttt{child}\}$. This, in turn makes `Mother` and `Grandmother` equivalent to `Woman`. As we can see, using this weaker notion of subsumption a whole branch of the hierarchy that used to describe different kinds of female parents collapses into a single concept with different names. With respect to our application that does not care about children, this is a wanted effect as we do not want to distinguish between different female persons on the basis of whether they have children or not.

3.2 Defining Viewpoints

As sketched in the motivation, each approximate subsumption operator defines a certain viewpoint on an ontology. In particular, it defines which aspects of a domain are relevant from the current point of view. If we chose the sub-vocabulary such that it does not contain the slot `has-gender` then we state that the corresponding aspect is not of interest for the particular viewpoint implemented by the subsumption operator. This basically means that we actually define a viewpoint in terms of a relevant part of the vocabulary. The corresponding subsumption operator serves as a tool for implementing this viewpoint. Based on this idea we define a viewpoint on an ontology as the set of subsumption relations that hold with respect to a certain sub-vocabulary.

Definition 4 (Viewpoint). *Let $V \subseteq \mathcal{V}$ a sub-vocabulary, then the viewpoint induced by sub-vocabulary V ($\mathcal{P}_V$) is defines as:*

$$\mathcal{P}_V = \{C \sqsubseteq D | C \underset{V}{\sqsubseteq} D\}$$

Example 1: Gender If we apply the above definition of a viewpoint on our example, we get a modified concept hierarchy, that reflects the corresponding viewpoint on the domain. For the case of the sub-vocabulary $\mathcal{V} - \{\texttt{has} - \texttt{gender}\}$ we get the hierarchy shown in figure 2.

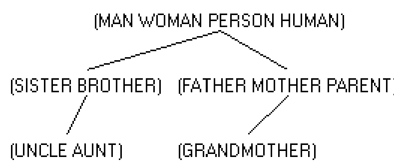

Fig. 2. The Hierarchy if we ignore the gender

If we compare this hierarchy with the original one shown in figure 1, we see that all distinctions that were based on the gender of a person have disappeared from the hierarchy. Now there is a single concept containing men, women, persons and humans a single class containing mothers, fathers and parents as well as a single concept containing brothers and sisters and a single class containing uncles and aunts.

Example: Children A similar observation can be made when looking at the viewpoint defined by the the sub-vocabulary $\mathcal{V} - \{\texttt{has} - \texttt{child}\}$. The concept hierarchy representing this viewpoint is shown in figure 3.

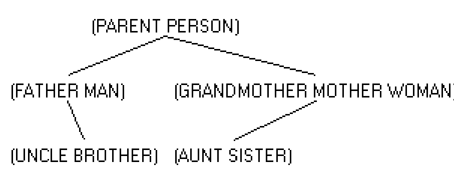

Fig. 3. The Example Ontology if we ignore children

Again, comparing this hierarchy to the original ontology shows that all distinctions that were based on the excluded property have disappeared from the hierarchy. In particular, the root of the hierarchy is now a concept that contains all people and all parents which are now indistinguishable. As in the previous example, this phenomenon occurs across the hierarchy as we now have a single class for women, mothers and grandmothers, a single class for men and fathers as well as a single class for brothers and uncles as well as for sisters and aunts.

4 Multi-Perspective Reasoning

The notion of subsumption with respect to a sub-vocabulary comes with new forms of reasoning. We can not longer only ask whether one concept subsumes another, but also whether it does with respect to a certain sub-vocabulary or ask for sub-vocabularies in which a concept subsumes another one. In the following, we first discuss some general properties of the subsumption operator introduced above that defines the relation between subsumption and sub-vocabularies. We then show how we can use the formal properties to efficiently compute viewpoints using sets of maximal vocabularies that ensure subsumption between a pair of concepts.

4.1 Axiomatic Properties of Limited Subsumption

The subsumption with respect to a sub-vocabulary operator has some general properties that we will exploit in the following to define the notion of viewpoint and to discuss the computation of different viewpoints. We briefly present these properties in the following without providing formal proofs, mainly because most of the properties are easy to see from the definition of subsumption with respect to a sub-vocabulary given above.

The first obvious property is the fact that subsumption with respect to the complete vocabulary is exactly the same as classical subsumption. The argument for this is straightforward as in that case, the set of concepts and relations to be removed from concept expressions is empty, so checking limited subsumption is just checking classical subsumption

$$C \underset{\mathcal{V}}{\sqsubseteq} D \Leftrightarrow C \sqsubseteq D \tag{1}$$

The properties above describe is an extreme cases of the framework where either the complete vocabulary is considered to be relevant. The interesting cases, however, are those where subsets of the vocabulary are considered. An interesting feature of the approach is that there is a direct correspondence between the relation between different sub-vocabularies and the limited forms of subsumption they define. In particular, the subsumption between two concepts with respect to a sub-vocabulary V_1 implies subsumption between the same concepts with respect to any subset V_2 of V_1.

$$C \underset{V_1}{\sqsubseteq} D \Rightarrow C \underset{V_2}{\sqsubseteq} D, \text{if } V_2 \subseteq V_1 \tag{2}$$

Another property is concerned with the transitivity of subsumption. It is quite obvious that if C subsumes D and D subsumes E with respect to the same sub-vocabulary, C also subsumes E with respect to this sub-vocabulary. We can generalize this to the case where subsumption relations between the concepts exist with respect to different sub-vocabularies V_1 and V_2.

$$C \underset{V_1}{\sqsubseteq} D \wedge D \underset{V_2}{\sqsubseteq} E \Rightarrow C \underset{V_1 \cap V_2}{\sqsubseteq} E \tag{3}$$

The previous property provides a basis for defining equivalence with respect to a subvocabulary. This basically is the special case of equation 3 where E is the same concept as C. In this case we say that C and D are equivalent with respect to the sub-vocabulary defined as the intersection of the two vocabularies in which one concept subsumes the other. The justification of thus axiom is exactly the same as for equation 3.

$$C \underset{V_1}{\sqsubseteq} D \wedge D \underset{V_2}{\sqsubseteq} C \Rightarrow C \underset{V_1 \cap V_2}{\equiv} D \tag{4}$$

As we will see in the following, these properties are quite useful with respect to defining different viewpoints and to determine important reasoning tasks in the context of multi-viewpoint reasoning.

4.2 Reasoning about Viewpoints

The reasoning tasks we have to consider in the context of multi-viewpoint representations are the same as for standard OWL ontologies. As in OWL, computing subsumption between two concept expressions is one of the basic reasoning tasks many other tasks such as classification and instance retrieval can be reduced to.

What makes reasoning in our framework different from standard reasoning is the fact that we have to deal with many different subsumption operators. In order to reduce the complexity of the task, we can refer to the axiomatic properties shown above and use the implications between subsumption statements to improve reasoning. If we know for example that C is subsumed by D with respect to the complete vocabulary, we do not have to check whether C subsumes D in any sub-vocabulary, as equation 2 tells us that this is always the case.

We can use the same equation to support the computation of a viewpoint. The idea is that in order to compute the viewpoint with respect to a sub-vocabulary V, we do not really have to check whether for each pair of concepts whether subsumption holds with respect to V. It is sufficient if we know that subsumption holds with respect to a larger sub-vocabulary $V' \supseteq V$. It is not directly evident why this helps to reduce reasoning effort as normally computing subsumption with respect to a larger vocabulary is more costly. We can make use of this property, however, if we know the maximal sub-vocabulary V for which $C \underset{V}{\sqsubseteq} D$

holds. In this case, we just have to test whether the current sub-vocabulary is a subset of the maximal vocabulary in order to decide conditional subsumption.

Definition 5 (Maximal Subsumption Vocabulary). *Let C and D be concept expressions. A sub-vocabulary $V \subseteq \mathcal{V}$ is called a maximal Subsumption Vocabulary for C and D if*

1. $C \underset{V}{\sqsubseteq} D$
2. *there is no* $V' \supset V$ *such that* $C \underset{V'}{\sqsubseteq} D$

Unfortunately, there is not always a unique maximal sub-vocabulary with the required properties. If we look at the following example, we see that C is subsumed by D with respect to $V = \{Q\}$ as $approx_{\{Q\}}(C) = approx_{\{Q\}}(D) = Q$ and that C is subsumed by D with respect to $V = \{R\}$, because in this case we have $approx_{\{R\}}(C) = approx_{\{R\}}(D) = \top \sqcap \exists R.\top$. At the same time, C is not subsumed by D with respect to $V = \{Q, R\}$ as we can easily see.

$$D \equiv Q \sqcap \exists R.Q \tag{5}$$

$$C \equiv Q \sqcap \exists R.(\neg Q) \tag{6}$$

Nevertheless, maximal sub-vocabularies, even though there may be more than one are important with respect to efficient reasoning about viewpoints. In particular, we can store a list of all maximal sub-vocabularies with reach pair of concepts and use equation 2 to test whether a given viewpoint is defined by a sub-vocabulary of one of the maximal ones stored. In this case, we know that C is subsumed by D in the current viewpoint.

This means that computing the set of maximal subsumption vocabularies for each pair of concepts is the primal reasoning task in the context of multi-viewpoint reasoning. In the following we provide a first algorithm for computing maximal subsumption vocabularies as a basis for more advanced reasoning tasks.

The algorithms computes for every pair C,D of concepts the set $MSV(C, D)$ of maximal Subsumption Vocabularies for C and D. This is done on the basis of a partial ordering of possible sub-vocabularies where the complete vocabulary is the first element in the order and sub-vocabularies are ordered by their cardinality. The algorithm now tests for each vocabulary if C is subsumed by D with respect to this vocabulary starting with the largest one. If this is the case, the vocabulary is added to $MSV(C, D)$ and all subsets of the vocabularies are removed from the order as they do not satisfy the second condition of definition 5. The result is a complete set of maximal subsumption vocabularies for each pair of concepts that can be used for efficiently checking the subsumption with respect to a certain sub-vocabulary. In particular, we can use the result of the algorithm to compute Viewpoints without actually computing subsumption. The corresponding algorithm is given below.

Algorithm 1 Maximal Subsumption Vocabulary (MSV)

Require: A set $\mathcal{C}$ of Concept Expressions over Vocabulary $\mathcal{V}$
Require: An ordering $(V_0, V_1, \cdots, V_m)$ on the subsets of $\mathcal{V}$ such that $V_0 = \mathcal{V}$ and $i < j \Rightarrow |V_i| > |V_j|$

```
for all {(C,D)|C,D ∈ 𝒞} do
  MSV(C,D) := ∅
  Cand(C,D) := (V_0, V_1, ··· , V_m)
  for all V ∈ Cand(C,D) do
    if approx_V(C) ⊑ approx_V(D) then
      MSV(C,D) := MSV(C,D) ∪ {V}
      Cand(C,D) := Cand(C,D) − {V'|V' ⊂ V}
    end if
  end for
end for
```

Algorithm 2 Viewpoint

Require: A set $\mathcal{C}$ of Concept Expressions over Vocabulary $\mathcal{V}$
Require: A subvocabulary $V \subseteq \mathcal{V}$

```
𝒫_V := ∅
for all {(C,D)|C,D ∈ 𝒞} do
  if ∃V' ∈ MSV(C,D) : V ⊂ V' then
    𝒫_V := 𝒫_V ∪ {C ⊆ D}
  end if
end for
```

The computation can further be optimized by using special index structures that already contain all subsets of $MSV(C, D)$. In this case, a viewpoint can be computed in linear time with respect to the number of concept pairs (quadratic with respect to the number of concepts). This means that based on a centralized generated index structure different applications can efficiently access their personal viewpoint of the model.

5 Discussion

In this paper, we proposed a model for representing and reasoning with multiple viewpoints in description logic ontologies. Our goal was to support the reuse of existing ontologies by applications that consider different aspects of the domain to be relevant. We have shown how we can deal with the case where a new application only considers a subset of the aspects encoded in the ontology relevant using an approximate subsumption operator that only takes a subset of the vocabulary into account.

If we really want to support the reuse of ontologies, we also have to take cases into account, where the aspects relevant to the new application are not a strict subset of the aspects covered by the ontology. In this case, the new aspects have to be integrated into the ontology. Currently this is often not done on the original ontology, because there is a danger of producing unwanted inconsistencies and to destroy existing subsumption relationships. Instead, a new ontology is created and customized to the needs of the new context. We think that the framework for multiple-viewpoints in ontologies can also help in this situation as it makes it possible to extend the original ontology with new aspects while still keeping it intact for its previous applications. The previous applications can just use the viewpoint that corresponds to the vocabulary that existed before the extension.

This possibility to keep one ontology and extend it for different purposes brings us closer to the idea of an ontology as a conceptualization that us actually shared between different applications. The use of viewpoints makes it possible to sign up for a common ontology without being forced to a viewpoint taken by other applications. This increases the chances of reducing the fragmentation of ontology development where a new ontology is created for every new application. The hope is, that the number of ontologies about a certain domain can be reduced to a number of models that represent completely non-compatible views on a domain while applications that have a different but compatible view on the domain use different viewpoints on the same ontology which evolves with every new application that introduces new aspects into the ontology.

From a theoretical point of view, the notion of approximate subsumption is a very interesting one. In this work, we chose a very specific definition and implementation of subsumption with respect to a sub-vocabulary. The definition was directly motivated by the aim to define different viewpoints on the same ontology. In future work we will aim at investigating approximate subsumption based on limited vocabularies in a more general setting. In particular, we will investigate a model-theoretic characterization of approximate subsumption in terms of weaker and stronger approximations (the work presented here is a special form of weaker approximation).

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