OWL FA: A Metamodeling Extension of OWL DL*

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ABSTRACT

This paper proposes OWL FA, a decidable extension of OWL DL with the metamodeling architecture of RDFS(FA). It shows that the knowledge base satisfiability problem of OWL FA can be reduced to that of OWL DL, and compares the FA semantics with the recently proposed contextual semantics and Hilog semantics for OWL.

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1. OWL AND METAMODELING

A common user complain about OWL DL is that it does not support metamodeling, which allows one to describe additional level(s) of classes and properties. In order to make use of (decidable) ontology reasoning, users has to restrict themselves into OWL DL. In practice, it is often not realistic to ask users to transfer their ontologies with meta-classes and meta-properties into ones without. Although OWL Full provides some metamodeling; however, it is not decidable. It has been pointed out that if we just ignore the need for metamodeling, some users will simply not use OWL, and the whole effort could become a failure [3].

Motik [1] proposes two alternative metamodeling approaches for OWL, i.e., the context approach and the HiLog approach. In the context approach, metamodeling is provided by allowing that the names for classes, properties and individuals are not distinguished from each other. The trick is to provide them different interpretation functions according to the context. Consequently, the interpretations of a class and an object sharing the same name are completely independent, which leads to non-intuitive result. For example, in this approach, if two objects `teacher` and `lecture` are asserted to be equivalent, the interpretation of the class `teacher` can be an empty set, while that of the class `lecture` can contain some objects, such as `Frank`. In the HiLog approach, the semantics is more intuitive; however, existing DL reasoners can not be reused, and one has to implement new reasoners.

This paper proposes OWL FA, an extension of OWL DL with the metamodeling architecture of RDFS(FA) [2]. There are two nice features of OWL FA. Firstly, it is a decidable extension of OWL DL. Secondly, the knowledge base satisfiability problem of OWl FA can be reduced to that of OWL DL, which indicates we can reuse existing DL reasoners to support OWL FA.

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2. OWL FA

Intuitively, OWL FA introduces a stratum number in class constructors and axioms to indicate the strata they belong to. Let i ≥ 0 be an integer. OWL FA consists of an alphabet of distinct class names $\mathbf{V}_{\mathrm{C_i}}$ (for stratum i), datatype names $\mathbf{V}_{\mathrm{D}}$, abstract property names $\mathbf{V}_{\mathrm{AP_i}}$ (for stratum i), datatype property names $\mathbf{V}_{\mathrm{DP}}$ and individual (object) names ($\mathbf{V}_{\mathrm{I}}$); together with a set of constructors (with subscriptions) to construct class and property descriptions (also called *OWL FA-classes* and *OWL FA-properties*, respectively).

OWL FA has a model theoretic semantics, which is regarded as an extension of that of RDFS(FA) with interpretations for OWL FA descriptions and axioms. In the rest of the paper, we assume that i is an integer such that $1 \leq \mathrm{i} \leq \mathrm{k}$. The interpretation function can be extended to give semantics to OWL FA-properties and OWL FA-classes. Let $RN \in \mathbf{V}_{\mathrm{AP_i}}$ be an abstract property name in stratum i and R an abstract property in stratum i. Valid OWL FA abstract properties are defined by the abstract syntax: $R ::= RN \mid R^-$, where for some $x, y \in \Delta_{A_{\mathrm{i}-1}^{\mathcal{J}}}$, $\langle x,y\rangle \in R^{\mathcal{J}}$ iff $\langle y,x\rangle \in R^{-\mathcal{J}}$. Valid OWL FA datatype properties are datatype property names.

Now we define the OWL FA-class descriptions. Let $\mathsf{CN} \in \mathbf{V}_{\mathrm{C_i}}$ be an atomic class name in stratum i, R an OWL FA-property in stratum i, $o \in \mathbf{I}$ an individual, $T \in \mathbf{V}_{\mathrm{DP}}$ a datatype property name, and C, D OWL FA-classes in stratum i. Valid OWL FA-classes are defined by the abstract syntax:

$$C \;::=\; \top_{\mathrm{i}} \mid \bot \mid \mathsf{CN} \mid \neg_{\mathrm{i}} C \mid C \sqcap_{\mathrm{i}} D \mid C \sqcup_{\mathrm{i}} D \mid \{o\} \mid \exists_{\mathrm{i}} R.C$$
$$\forall_{\mathrm{i}} R.C \mid \leqslant_{\mathrm{i}} nR \mid \geqslant_{\mathrm{i}} nR$$
$$\text{(if i = 1) } \exists_1 T.d \mid \forall_1 T.d \mid \leqslant_1 nT \mid \geqslant_1 nT$$

The semantics of OWL FA-classes are presented in Table 1 (page). C is *satisfiable* iff there exist an interpretation $\mathcal{J}$ s.t. $C^{\mathcal{J}} \neq \emptyset$; C subsumes D iff for every interpretation $\mathcal{J}$ we have $C^{\mathcal{J}} \subseteq D^{\mathcal{J}}$.

An OWL FA knowledge base Σ consists of $\Sigma_1, \ldots, \Sigma_k$. Each Σ_{i} consists of a TBox $\mathcal{T}_{\mathrm{i}}$, an RBox $\mathcal{R}_{\mathrm{i}}$ and an ABox $\mathcal{A}_{\mathrm{i}}$. Due to the limitation of space, we only present class and individual axioms here, and leave out the property axioms in RBoxes. An OWL FA *TBox* $\mathcal{T}_{\mathrm{i}}$ is a finite set of class inclusion axioms of the form $C \sqsubseteq_{\mathrm{i}} D$, where C, D are OWL FA-classes in stratum i. An interpretation $\mathcal{J}$ satisfies $C \sqsubseteq_{\mathrm{i}} D$ if $C^{\mathcal{J}} \subseteq D^{\mathcal{J}}$.

Let $\mathsf{a}, \mathsf{b} \in \mathbf{I}$ be individuals, C_1 a class in stratum 1, R_1 an abstract property in stratum 1, l a literal, $T \in \mathbf{V}_{\mathrm{D}}$ a datatype property, X, Y classes or abstract properties in stratum i, E a class in stratum i + 1 and S an abstract property in stratum i+1. An OWL FA *ABox* $\mathcal{A}_1$ is a finite set of individual axioms of the following forms:

Constructor	DL Syntax	Semantics
top	$\top_{\mathrm{i}}$	$\Delta_{A_{\mathrm{i}-1}}^{\mathcal{J}}$
bottom	$\bot$	$\emptyset$
concept name	CN	$\mathsf{CN}^{\mathcal{J}} \subseteq \Delta_{A_{\mathrm{i}-1}}^{\mathcal{J}}$
general negation	$\neg_{\mathrm{i}} C$	$\Delta_{A_{\mathrm{i}-1}}^{\mathcal{J}} \setminus C^{\mathcal{J}}$
conjunction	$C \sqcap_{\mathrm{i}} D$	$C^{\mathcal{J}} \cap D^{\mathcal{J}}$
disjunction	$C \sqcup_{\mathrm{i}} D$	$C^{\mathcal{J}} \cup D^{\mathcal{J}}$
nominals	$\{\mathsf{o}\}$	$\{\mathsf{o}\}^{\mathcal{J}} = \{\mathsf{o}^{\mathcal{J}}\}$
exists restriction	$\exists_{\mathrm{i}} R.C$	$\{x \in \Delta_{A_{\mathrm{i}-1}}^{\mathcal{J}} \mid \exists y.\langle x, y\rangle \in R^{\mathcal{J}} \wedge y \in C^{\mathcal{J}}\}$
value restriction	$\forall_{\mathrm{i}} R.C$	$\{x \in \Delta_{A_{\mathrm{i}-1}}^{\mathcal{J}} \mid \forall y.\langle x, y\rangle \in R^{\mathcal{J}} \rightarrow y \in C^{\mathcal{J}}\}$
atleast restriction	$\geqslant_{\mathrm{i}} mR$	$\{x \in \Delta_{A_{\mathrm{i}-1}}^{\mathcal{J}} \mid \sharp\{y \mid \langle x, y\rangle \in R^{\mathcal{J}}\} \geq m\}$
atmost restriction	$\leqslant_{\mathrm{i}} mR$	$\{x \in \Delta_{A_{\mathrm{i}-1}}^{\mathcal{J}} \mid \sharp\{y \mid \langle x, y\rangle \in R^{\mathcal{J}}\} \leq m\}$
datatype exists	$\exists_1 T.d$	$\{x \in \Delta_{A_0}^{\mathcal{J}} \mid \exists t.\langle x, t\rangle \in T^{\mathcal{J}} \wedge t \in d^{\mathcal{J}}\}$
datatype value	$\forall_1 T.d$	$\{x \in \Delta_{A_0}^{\mathcal{J}} \mid \forall t.\langle x, t\rangle \in T^{\mathcal{J}} \rightarrow t \in d^{\mathcal{J}}\}$
datatype atleast	$\geqslant_1 mT$	$\{x \in \Delta_{A_0}^{\mathcal{J}} \mid \sharp\{t \mid \langle x, t\rangle \in T^{\mathcal{J}}\} \geq m\}$
datatype atmost	$\leqslant_1 mT$	$\{x \in \Delta_{A_0}^{\mathcal{J}} \mid \sharp\{t \mid \langle x, t\rangle \in T^{\mathcal{J}}\} \leq m\}$

Table 1: OWL FA classes

$\mathtt{a} :_1 C_1$, called *class assertions*, $\langle \mathtt{a}, \mathtt{b}\rangle :_1 R_1$, called *abstract property assertions*, $\langle \mathtt{a}, l\rangle :_1 T$, called *datatype property assertions*, $\mathtt{a} = \mathtt{b}$, called *individual equality axioms* and , $\mathtt{a} \neq \mathtt{b}$, called *individual inequality axioms*. An interpretation $\mathcal{J}$ satisfies $\mathtt{a} :_1 C_1$ if $\mathtt{a}^{\mathcal{J}} \in C_1^{\mathcal{J}}$; it satisfies $\langle \mathtt{a}, \mathtt{b}\rangle :_1 R_1$ if $\langle \mathtt{a}^{\mathcal{J}}, \mathtt{b}^{\mathcal{J}}\rangle \in R_1^{\mathcal{J}}$; it satisfies $\langle \mathtt{a}, l\rangle :_1 T$ if $\langle \mathtt{a}^{\mathcal{J}}, l^{\mathcal{J}}\rangle \in T^{\mathcal{J}}$; it satisfies $\mathtt{a} = \mathtt{b}$ if $\mathtt{a}^{\mathcal{J}} = \mathtt{b}^{\mathcal{J}}$; it satisfies $\mathtt{a} \neq \mathtt{b}$ if $\mathtt{a}^{\mathcal{J}} \neq \mathtt{b}^{\mathcal{J}}$. An OWL FA *ABox* $\mathcal{A}_{\mathrm{i}}$ is a finite set of axioms of the following forms: $X : E$, called *meta-class assertions*, $\langle X, Y\rangle : R$, called *meta-property assertions*, or $X =_{\mathrm{i}-1} Y$, called *meta individual equality axioms*. An interpretation $\mathcal{J}$ satisfies $X : E$ if $X^{\mathcal{J}} \in E^{\mathcal{J}}$; it satisfies $\langle X, Y\rangle : R$ if $\langle X^{\mathcal{J}}, Y^{\mathcal{J}}\rangle \in R^{\mathcal{J}}$; it satisfies $X =_{\mathrm{i}-1} Y$ if $X^{\mathcal{J}} = Y^{\mathcal{J}}$.

An interpretation $\mathcal{J}$ satisfies a knowledge base Σ if it satisfies all the axioms in Σ. Σ is *satisfiable* (*unsatisfiable*) iff there exists (does not exist) such an interpretation $\mathcal{J}$ that satisfies Σ. Let C, D be OWL FA-classes in stratum i, C is *satisfiable* w.r.t. Σ iff there exist an interpretation $\mathcal{J}$ of Σ s.t. $C^{\mathcal{J}} \neq \emptyset_{\mathrm{i}}$; C subsumes D w.r.t. Σ iff for every interpretation $\mathcal{J}$ of Σ we have $C^{\mathcal{J}} \subseteq D^{\mathcal{J}}$.

Example 1 Here we represent a meta part of WordNet ontology in the following OWL FA axioms.

$$\exists_2(\mathtt{wns}{:}\textit{hyponymOf}) \sqsubseteq_2 \mathtt{wns}{:}\mathsf{LexicalConcept}$$
$$\exists_2(\mathtt{wns}{:}\textit{hyponymOf})^- \sqsubseteq_2 \mathtt{wns}{:}\mathsf{LexicalConcept}$$
$$\langle \mathtt{wnc{:}100002086}, \mathtt{wnc{:}100001740}\rangle :_2 (\mathtt{wns}{:}\textit{hyponymOf})$$
$$\mathtt{wns}{:}\mathsf{Adverb} \sqsubseteq_2 \mathtt{wns}{:}\mathsf{LexicalConcept}$$
$$\mathtt{wns}{:}\mathsf{Adverb} \sqsubseteq_2 \neg_2(\mathtt{wns}{:}\mathsf{Noun\_and\_Verb})$$
$$\mathrm{Trans}_2(\mathtt{wns}{:}\textit{hyponymOf})$$

Now we briefly discuss some reasoning tasks of OWL FA. In an OWL FA knowledge base Σ, it is obvious that Σ_1 is a $\mathcal{SHOIN}(\mathbf{D})$ knowledge base, and $\Sigma_2, \ldots, \Sigma_{\mathrm{k}}$ are $\mathcal{SHIQ}$ knowledge bases. Note that classes and property names in Σ_{i} are treated as individual names in $\Sigma_{\mathrm{i}+1}$; therefore, class and property equality axioms in Σ_{i} can act as individual equality axioms in $\Sigma_{\mathrm{i}+1}$. On the other hand, individual equalities explicitly asserted and implicitly entailed by number restrictions in $\Sigma_{\mathrm{i}+1}$ can act as class and property equality axioms in Σ_{i}.

Definition 2 Let $\Sigma = \langle \Sigma_1, \ldots, \Sigma_{\mathrm{k}}\rangle$ be an OWL FA knowledge base, where each of $\Sigma_1, \ldots, \Sigma_{\mathrm{k}}$ is consistent. $\Sigma^* = \langle \Sigma_1^*, \ldots, \Sigma_{\mathrm{k}}^*\rangle$, called the *explicit knowledge base*, is constructed by making all the implicit atomic class axioms, atomic property axioms and individual equality axioms explicit. ⋄

As we have a finite set of vocabulary, we have the following Lemma.

Lemma 3 Given an OWL FA knowledge base $\Sigma = \langle \Sigma_1, \ldots, \Sigma_{\mathrm{k}}\rangle$. Σ^* can be constructed from Σ in finite steps.

It can be argued that, in many realistic ontologies, Σ^* would *not* be much bigger than Σ. This is based on the observation that the number of entailed but not explicit stated equal class (property, individual) pairs would not be huge (as usually it is not extremely helpful to have multiple class names for the same class description). On the other hand, the entailed equalities often come as a surprise for ontology builders.

Note that if a class description is not defined in $\Sigma_{\,i}$ (i.e., if it is not equivalent to any atomic class), it is not represented by any meta-individual in $\Sigma_{\,i+1}$. This suggests the connections between $\Sigma_{\,i}$ and $\Sigma_{\,i+1}$ are atomic classes and properties in $\Sigma_{\,i}$, which are meta-individuals in $\Sigma_{\,i+1}$. Accordingly, once we calculate the explicit knowledge bases, we can decide the knowledge base satisfiability problems locally.

Theorem 4 Given an OWL FA knowledge base $\Sigma = \langle \Sigma_1, \ldots, \Sigma_{\mathrm{k}}\rangle$. Σ is satisfiable iff each Σ_{i}^* ($1 \leq \mathrm{i} \leq \mathrm{k}$) is satisfiable.

Theorem 4 indicates we can reduce the OWL FA-knowledge base satisfiability problem to the OWL DL-knowledge base satisfiability problem.

3. CONCLUSION AND OUTLOOK

In this paper, we propose the OWL FA ontology language as a decidable metamodeling extension of OWL DL. The syntax of OWL FA is very similar to that of OWL DL; it introduces a stratum number to attach to OWL FA class constructors and axioms. These numbers can be hidden by tools from the users. The semantics of OWL FA is a natural extension of that of OWL DL, dividing the abstract domain into k sub-domains for k strata.

We have shown that it is possible to make use of existing OWL DL reasoners to reason with OWL FA knowledge bases. Most importantly, we believe that reasoning in OWL FA is not much harder than OWL DL. Firstly, as argued in the previous section, the explicit knowledge base Σ^* usually would not be much bigger than the original knowledge base Σ. Furthermore, we can often assume that the meta knowledge bases $\Sigma_2, \ldots, \Sigma_{\mathrm{k}}$ are more stable and much smaller than Σ_1. Indeed, when $\Sigma_2, \ldots, \Sigma_{\mathrm{k}}$ are much simpler and smaller than Σ_1, the reasoning time for much smaller than Σ_1, the reasoning time spent on $\Sigma_2, \ldots, \Sigma_{\mathrm{k}}$ can be ignored to some extent. This suggest a clear advantage of the FA semantics over the HiLog semantics [1], which requires implementations of new reasoners to provide research services.

In the future, we plan to implement the construction of explicit knowledge bases so that we can use OWL DL reasoners to reason with OWL FA knowledge bases, and to evaluate it with, for example, the WordNet ontology.

4. REFERENCES

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