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An Extensible Approach for Modeling Ontologies in RDF(S)

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Abstract. RDF(S)[1] constitutes a newly emerging standard for metadata that is about to turn the World Wide Web into a machine-understandable knowledge base. It is an XML application that allows for the denotation of facts and schemata in a web-compatible format, building on an elaborate object-model for describing concepts and relations. Thus, it might turn up as a natural choice for a widely-useable ontology description language. However, its lack of capabilities for describing the semantics of concepts and relations beyond those provided by inheritance mechanisms makes it a rather weak language for even the most austere knowledge-based system. This paper presents an approach for modeling ontologies in RDF(S) that also considers axioms as objects that are describable in RDF(S). Thus, we provide flexible, extensible, and adequate means for accessing and exchanging axioms in RDF(S). Our approach follows the spirit of the World Wide Web, as we do not assume a global axiom specification language that is too intractable for one purpose and too weak for the next, but rather a methodology that allows (communities of) users to specify what axioms are interesting in their domain.

1 Introduction

The development of the World Wide Web is about to mature from a technical platform that allows for the transportation of information from sources to humans (albeit in many syntactic formats) to the communication of knowledge from Web sources to machines. The knowledge food chain has started with technical protocols and preliminary formats for information presentation (HTML – HyperText Markup Language) over a general methodology for separating information contents from layout (XML – eXtensible Markup Language, XSL – eXtensible Stylesheet Language) to reach the realms of knowledge provisioning by the means of RDF and RDFS.

RDF (Resource Description Framework) is a W3C recommendation [12] that provides description facilities for knowledge pieces, *viz.* for triples that denote relations between pairs of objects. To exchange and process RDF models they can be serialized in XML. RDF exploits the means of XML to allow for disjoint namespaces, linking and referring between namespaces and, hence, is a general methodology for sharing machine-processable knowledge in a distributed setting. On top of RDF the simple schema language *RDFS* (Resource Description Framework Schema; [2]) has been defined to offer a distinguished vocabulary to model class and property hierarchies and other basic schema primitives that can be refered to from RDF models. To phrase the role of RDFS in knowledge engineering terminology, it defines a simple *ontology* that particular RDF documents may be checked against to determine consistency.

Ontologies have shown their usefulness in application areas such as intelligent information integration or information brokering. Therefore their use is highly interesting for web applications, which may also profit from long term experiences made in the knowledge acquisition community. At the same time, this is a great chance for the knowledge acquisition community as RDF(S) may turn knowledge engineering, so far a niche technology, into a technological and methodological powerhouse. Nevertheless, while support for modeling of ontological concepts and relations has been extensively provided in RDF(S), the same cannot be said about the modeling of ontological axioms — one of the key ingredients in ontology definitions and one of the major benefits of ontology applications.

RDF(S) offers only the most basic modeling primitives for ontology modeling. Even though there are good and bad choices for particular formal languages, one must face the principal trade-off between tractability and expressiveness of a language. RDF(S) has been placed nearer to the low end of expressiveness, because it has been conceived to be applica-

[1] We use "RDF(S)" to refer to the combined technologies of RDF and RDF-Schema.

ble to vast web resources! In contrast to common knowledge representation languages, RDF(S) has not been meant to be the definitive answer to all knowledge representation problems, but rather an *extensible core language*. The namespace and reification mechanisms of RDF(S) allow (communities of) users to define their very own standards in RDF(S) format — extending the core definitions and semantics. As RDF(S) leaves the well-trodden paths of knowledge engineering at this point, we must reconsider crucial issues concerning ontology modeling and ontology applications. To name but a few, we mention the problem of merging and mapping between namespaces, scalability issues, or the definition and usage of ontological axioms.

In this paper we concentrate on the latter, namely on how to model axioms in RDF(S) following the stipulations, *(i)*, that the core semantics of RDF(S) is re-used such that "pure" RDF(S) applications may still process the core object-model definitions, *(ii)*, that the semantics is preserved between different inferencing tools (at least to a large stretch), and, *(iii)*, that axiom modeling is adaptable to reflect diverging needs of different communities. Current proposals neglect or even conflict with one or several of these requirements. For instance, the first requirement is violated by the ontology exchange language XOL [10] making *all* the object-model definitions indigestible for most RDF(S) applications. The interchangeability and adaptability stipulation is extremely difficult to meet by the parse-tree-based representation of MetaLog [14], since it obliges to first-order logic formulae. We will show how to adapt a general methodology that we have proposed for axiom modeling [13,15] to be applied to the engineering of ontologies with RDF(S). Our approach is based on translations of RDF(S) axiom specifications into various target systems that provide the inferencing services. As our running example, we map axiom specifications into an F-Logic format that has already served as the core system for SiLRi, an inference service for core RDF [4]. Our methodology is centered around categorization of axioms, because this allows for a more concise description of the *semantic meaning* rather than a particular syntactic representation of axioms. Thus, we get a better grip on extensions and adaptations to particular target inferencing systems.

In the following, we introduce the RDF(S) data model and describe how to define an object model in RDF(S) including practical issues of ontology documentation (Section 2). Then we describe our methodology for using RDF(S) such that axioms may be engineered and exchanged. We describe the core idea of our approach and illustrate with several examples how to realize our approach (Section 3). Before we conclude, we give a brief survey of related work.

2 Modeling Concepts and Relations in RDF(S)

In this section we will first take a look at the core ontology engineering task, i.e. at the RDF(S) data model proper, and then exploit RDF(S) also for purposes of practical ontology engineering, viz. for documentation of newly defined or reused ontologies. This will lay the groundwork for the modeling of axioms in Section 3.

2.1 The RDF(S) Data Model

RDF(S) is an abstract data model that defines relationships between entities (called resources in RDF) in a similar fashion as semantic nets. Statements in RDF describe resources, that can be web pages or surrogates for real world objects like publications, pieces of art, persons, or institutions. We illustrate how concepts and relations can be modelled in RDF(S) by presenting a sample ontology in the abstract data model and only afterwards show how these concepts and relations are presented in the XML-serialisation of RDF(S).

2.1.1 RDF

As already mentioned RDF(S) consists of two closely related parts: RDF and RDF Schema. The foundation of RDF(S) is laid out by RDF which defines basic entities, like resources, properties, and statements. Anything in RDF(S) is a resource. Resources may be related to each other or to literal (i.e. atomic) values via properties. Such a relationship represents a statement that itself may be considered a resource, i.e. reification is directly built into the RDF data model. Thus, it is possible to make statements about statements. These basic notions can be easily depicted in a graphical notation that resembles semantic nets. To illustrate the possibilities of pure RDF the following statements are expressed in RDF and depicted in Figure 1[2]:

- Firstly, in part (a) of Figure 1 two resources are defined, each carrying a FIRSTNAME and a LASTNAME property with literal values, identifying the resources as William and Susan Smith, respectively. These two resources come with a URI as their unique global identifier and they are related via the property MARRIEDWITH, which expresses that William is married with Susan.
- Part (b) of the illustration shows a convenient shortcut for expressing more complex statements, i.e. reifying a statement and defining a property for the new resource. The example denotes that the marriage between William and Susan has been confirmed by the resource representing the Holy Father in Rome.
- The RDF data model offers the predefined resource `rdf:statement` and the predefined properties `rdf:subject`, `rdf:predicate`, and `rdf:object` to reify a statement as a resource. The actual model for the example (b) is depicted in part (c) of Figure 1. Note that the reified statement makes no claims about the truth value of what is reified, i.e. if one wants to express that William and Susan are married *and* that this marriage has been confirmed by the pope then the actual data model must contain a union of part (a) and part (c) of the example illustration.

[2] Resources are represented by shaded rectangles, literal values by ovals and properties by directed, labeled arcs.

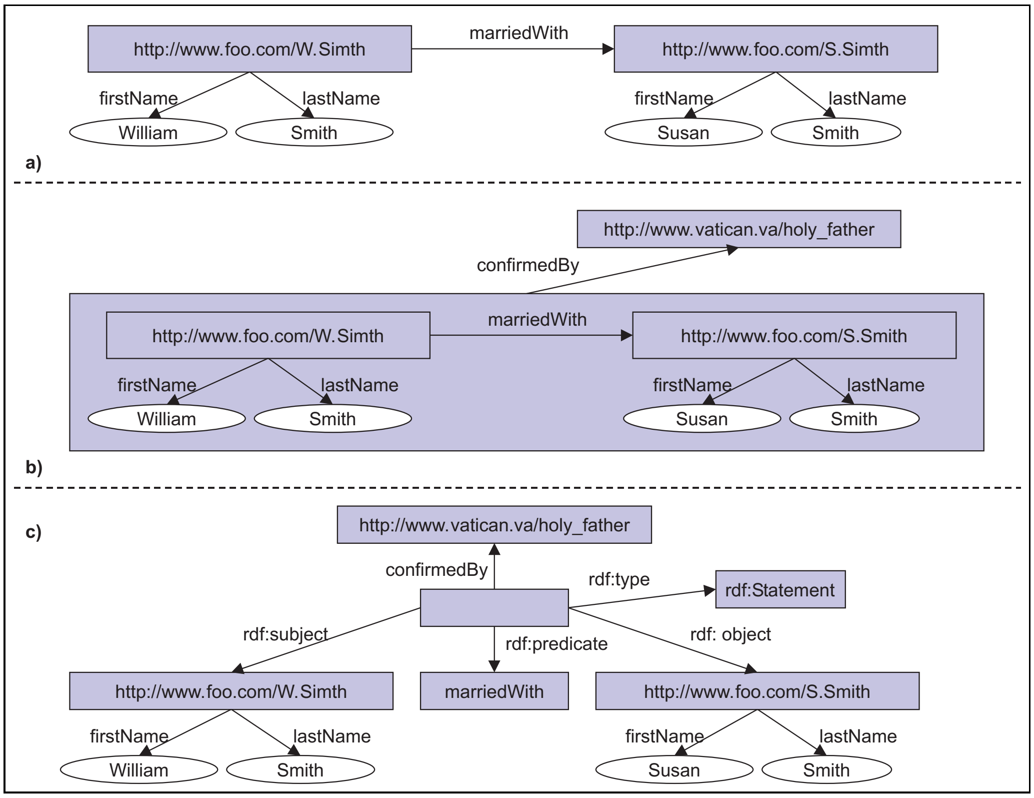

Fig. 1. An example RDF data model.

2.1.2 RDFS

As a companion standard to RDF the schema language RDFS is more important with respect to ontological modeling of domains. RDFS offers a distinguished vocabulary defined on top of RDF to allow the modelling of object models with cleanly defined semantics. The terms introduced in RDFS build the groundwork for the extensions of RDF(S) that are proposed in this paper. The relevant RDFS terms are presented in the following list.

- The most general class in RDF(S) is `rdfs:Resource`. It has two subclasses, namely `rdfs:Class` and `rdf:Property` (cf. Figure 2[3]). When specifying a domain specific schema for RDF(S), the classes and properties defined in this schema will become instances of these two resources.
- The resource `rdfs:Class` denotes the set of all classes in an object-oriented sense. That means, that classes like `appl:Person` or `appl:Organisation` are instances of the meta-class `rdfs:Class`.
- The same holds for properties, i.e. each property defined in an application specific RDF schema is an instance of `rdf:Property`, e.g. `appl:marriedWith`
- RDFS defines the special property `rdfs:subClassOf` that defines the subclass relationship between classes. Since `rdfs:subClassOf` is transitive, definitions are inherited by the more specific classes from the more general classes and resources that are instances of a class are automatically instances of all superclasses of this class. In RDF(S) it is prohibited that any class is an `rdfs:subClassOf` itself or of one of its subclasses.
- Similar to `rdfs:subClassOf`, which defines a hierarchy of classes, another special type of relation `rdfs:subPropertyOf` defines a hierarchy of properties, e.g. one may express that FATHEROF is a `rdfs:subPropertyOf` PARENTOF.
- RDFS allows to define the domain and range restrictions associated with properties. For instance, these restrictions allow the definition that persons and only persons may be MARRIEDWITH and only with other persons.

As depicted in the middle layer of Figure 2 the domain specific classes `appl:Person`, `appl:Man`, and `appl:Woman` are defined as instances of `rdfs:Class`. In the same way domain specific property types are defined as instances of `rdf:Property`, i.e. APPL:MARRIEDWITH, APPL:FIRSTNAME, and APPL:LASTNAME.

2.1.3 The use of XML Namespaces in RDF(S).

The XML namespace mechanism plays a crucial role for the development of RDF schemata and applications. It allows to distinguish between different modeling layers (cf. Figure 2 and 3) and to reuse and integrate existing schemata and appli-

[3] The reader may note that only a very small part of RDF(S) is depicted in the RDF/RDFS layer of the figure. Furthermore, the relation APPL:MARRIEDWITH in the data layer is identical to the resource APPL:MARRIEDWITH in the schema layer.

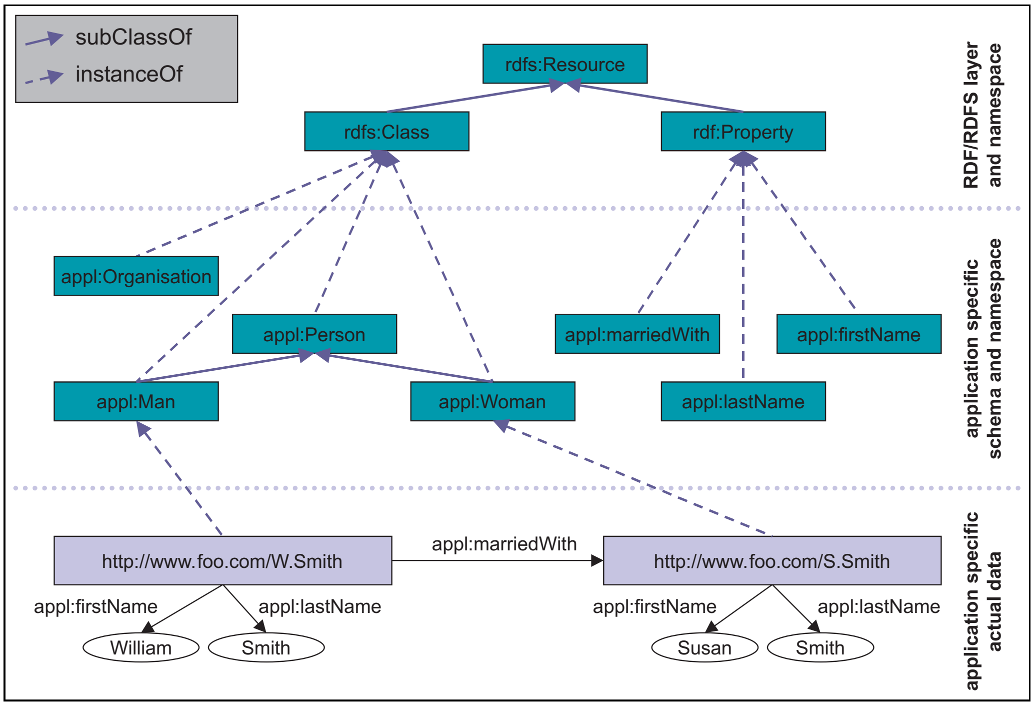

Fig. 2. An example RDF schema and its embedding in RDF(S).

cations. At the time being, there exist a number of *canonical* namespaces, e.g. for RDF, RDFS, and Dublin Core (cf. Section 2.2). We here introduce two new namespaces that aim at two different objectives, viz. the comprehensive documentation of ontologies and the capturing of our proposal for the modeling of ontological axioms

An actual ontology definition occurs at a concrete URL[4]. It defines shorthand notations which refer to our actual namespaces for ontology documentation and modeling of ontological axioms, abbreviated `odoc` and `o`, respectively. An actual application that uses our example ontology will define a shorthand identifier like `appl` in order to refer to this particular, application-specific ontology. Figures 2 and 3 presume these shorthand notations for the namespaces we have just mentioned.

2.1.4 XML serialization of RDF(S).

One important aspect for the success of RDF in the WWW is the way RDF models are represented and exchanged, namely via XML. In the following excerpt of the RDF schema document `http://ontoserver.aifb.uni-karlsruhe.de/schema/example.rdf`, the classes and property types defined in Figure 2 are represented in XML and the domains and ranges of the properties are defined using the RDF constraint properties `rdfs:domain` and `rdfs:range`.

```
<rdf:Description ID="Person">
 <rdf:type resource="http://www.w3.org/TR/1999/PR-rdf-
schema-19990303#Class"/>
 <rdfs:subClassOf
    rdf:resource="http://www.w3.org/TR/1999/PR-rdf-
schema-19990303#Resource"/>
</rdf:Description>

<rdf:Description ID="Man">
 <rdf:type resource="http://www.w3.org/TR/1999/PR-rdf-
schema-19990303#Class"/>
 <rdfs:subClassOf rdf:resource="#Person"/>
</rdf:Description>

<rdf:Description ID="Woman">
 <rdf:type resource="http://www.w3.org/TR/1999/PR-rdf-
schema-19990303#Class"/>
 <rdfs:subClassOf rdf:resource="#Person"/>
</rdf:Description>

<rdf:Description ID="Organisation">
 <rdf:type resource="http://www.w3.org/TR/1999/PR-rdf-
schema-19990303#Class"/>
 <rdfs:subClassOf
    rdf:resource="http://www.w3.org/TR/1999/PR-rdf-
schema-19990303#Resource"/>
</rdf:Description>

<rdf:Description ID="firstName">
 <rdf:type
    resource="http://www.w3.org/TR/1999/PR-rdf-
schema-19990303#Property"/>
 <rdfs:domain rdf:resource="#Person"/>
 <rdfs:range rdf:resource="http://www.w3.org/TR/
xmlschema-2/#string"/>
</rdf:Description>

<rdf:Description ID="lastName">
 <rdf:type
    resource="http://www.w3.org/TR/1999/PR-rdf-
schema-19990303#Property"/>
 <rdfs:domain rdf:resource="#Person"/>
 <rdfs:range rdf:resource="http://www.w3.org/TR/
xmlschema-2/#string"/>
</rdf:Description>

<rdf:Description rdf:ID="marriedWith">
 <rdf:type
    resource="http://www.w3.org/TR/1999/PR-rdf-
schema-19990303#Property"/>
```

[4] The reader may actually compare with the documents that appear at these URLs, e.g. `http://ontoserver.aifb.uni-karlsruhe.de/schema/example.rdf`

```
 <rdfs:domain rdf:resource="#Person"/>
 <rdfs:range rdf:resource="#Person"/>
</rdf:Description>
```

2.2 *Modeling ontology metadata using RDF Dublin Core*

Metadata about ontologies, such as the title, authors, version, statistical data, etc. are important for practical tasks of ontology engineering and exchange. In our approach we have adopted the well-established and standardized RDF Dublin Core Metadata element set [16]. This element set comprises fifteen elements which together capture basic aspects related to the description of resources. Ensuring a maximal level of generality and exchangeability, our ontologies are labeled using this basic element set. Since ontologies represent a very particular class of resource, the general Dublin Core metadata description does not offer sufficient support for ontology engineering and exchange. Hence, we describe further semantic types in the schema located at `http://ontoserver.aifb.uni-karlsruhe.de/schema/ontodoc`
and instantiate these types when we build a new ontology. The example below illustrates our usage and extension of Dublin Core by an excerpt of an exemplary ontology metadata description.

```
<?xml version='1.0' encoding='ISO-8859-1'?>
<rdf:RDF xmlns:rdf = "http://www.w3.org/1999/02/22-rdf-
syntax-ns#"
  xmlns:dc = "http://purl.oclc.org/dc"
  xmlns:odoc =
"http://ontoserver.aifb.uni-karlsruhe.de/schema/ontodoc">

  <rdf:Description about = "">
    <dc:Title>An Example Ontology</dc:Title>
    <dc:creator>
        <rdf:Bag>
           <rdf:li>Steffen Staab</rdf:li>
           <rdf:li>Michael Erdmann</rdf:li>
           <rdf:li>Alexander Maedche</rdf:li>
           <rdf:li>Stefan Decker</rdf:li>
        </rdf:Bag>
    </dc:creator>
    <dc:date>2000-02-29</dc:date>
    <dc:format>text/xml</dc:format>
    <dc:description>
        An example ontology modeled for this small
        application
    </dc:description>
    <dc:subject>Ontology, RDF</dc:subject>

    <odoc:url>
    http://ontoserver.aifb.uni-karlsruhe.de/sche-
          ma/example.rdf
    </odoc:url>
    <odoc:version>2.1</odoc:version>
    <odoc:last_modification>2000-03-01
    </odoc:last_modification>
    <odoc:ka_technique>
    semi-automatic text knowledge acquisition
    </odoc:ka_technique>
    <odoc:ontology_type>domain ontology
    </odoc:ontology_type>
    <odoc:no_concepts>24</odoc:no_concepts>
    <odoc:no_relations>23</odoc:no_relations>
    <odoc:no_axioms>11</odoc:no_axioms>
    <odoc:highest_depth_level>6
    </odoc:highest_depth_level>
  </rdf:Description>
</rdf:RDF>
```

3 Modeling of Axioms in RDF(S)

Having prepared the object-model and documentation backbone for ontologies in RDF(S), we may now approach the third pillar of our approach, viz. the specification of axioms in RDF(S). The basic idea that we pursue is the specification and serialization of axioms in RDF(S) such that they remain easily representable and exchangeable between different ontology engineering, representation and inferencing environments. The principal specification needs to be rather independent of particular target systems (to whatever extent this is possible at all) in order to be of value in a distributed web setting with many different basic applications.

3.1 *Axioms are Objects, too*

Representation of interesting axioms that are deemed to be applied in different inferencing applications turns out to be difficult. The reason is that typically some kind of non-propositional logic is involved that deals with quantifiers and quantifier scope. Axioms are difficult to grasp, since the representation of quantifier scope and its likes is usually what the nitty-gritty details of a particular syntax, on which a particular inferencing application is based, are about. An ontology representation in RDF(S) should, however, abstract from particular target systems.

A closer look at the bread and butter issues of ontology modeling reveals that many axioms that need to be formulated aim at much simpler purposes than arbitrary logic structures. Indeed, we have found that many axioms in our applications belong to one of a list of major axiom categories:

1. Axioms for a relational algebra
   (a) Reflexivity of relations
   (b) Irreflexivity of relations
   (c) Symmetry of relations
   (d) Asymmetry of relations
   (e) Antisymmetry of relations
   (f) Transitivity of relations
   (g) Inverse relations
2. Composition of relations[5]
3. (Exhaustive) Partitions[6]
4. Axioms for subrelation relationships
5. Axioms for part-whole reasoning

Our principal idea for representing ontologies with axioms in RDF(S) is based on this categorization. The categories allow to distinguish between the structures that are repeatedly found in axiom specifications from a corresponding description in a particular language. Hence, one may describe axioms as complex objects (one could term them instantiations of axiom schemata) in RDF(S) that refer to concepts and relations, which are also denoted in RDF(S). For sets of axiom types we presume the definition of different

[5] E.g., FATHERINLAWOF is composed by the relations FATHEROF and MARRIEDWITH.

[6] E.g., concepts *Man* and *Woman* share no instances.

RDF schemata. Similar to the case of simple metadata structures, the RDF schema responsible for an axiom categorization obliges to a particular semantics of its axiom types — which may be realized in a number of different inferencing systems like description logics systems (e.g., [8]) or frame logic systems [4]. The schema defined in our namespace `http://ontoserver.aifb.uni-karlsruhe.de/schema/ontordf` stands for the semantics defined in this and our previous papers [13, 15].[7] The schema is also listed in the appendix of this paper (cf. Section A). Other communities may, of course, find other reasoning schemes more important, or they may just need an extension compared to what we provide here.

Thus, we build a two-layer approach. On the first layer, the *symbol level*, we provide a RDF(S) syntax (i.e. serialization) to denote particular types of axioms. The categorization really constitutes a *knowledge level* that is independent from particular machines. In order to use an ontology denoted with our RDF(S) approach, one determines the appropriate axiom category and its actual instantiation found in a RDF(S) piece of ontology, translates it into a corresponding logical representation and executes it by an inferencing engine that is able to reason with (some of) the relevant axiom types.

Figure 3 summarizes our approach for modeling axiom specifications in RDF(S). It depicts the core of the RDF(S) definitions and our extension for axiom categorizations (i.e. our ontology meta layer). A simple ontology, especially a set of application specific relationships, is defined in terms of our extension to RDF(S).

In the following subsections, we will further elucidate our approach by proceeding through a few simple examples of our categorization of axiom specifications listed above. In particular our scheme is, *(A)* to show the representations of axioms in RDF(S) and *(B)* to show a structurally equivalent F(rame)-Logic representation that may easily be derived from its RDF(S) counterpart (cf. [11, 3] on F-Logic). Then, *(C)* we exploit the expressiveness of F-Logic in order to specify translation axioms that work directly on the F-Logic object representation of axioms. Thus, *(B)* in combination with *(C)* describes a formally concise and executable translation. For better illustration, we finally, *(D)*, indicate the result of our translation by exemplary target representations of the axioms stated in RDF(S).

The reader should note here that we do neither believe that F-Logic fulfills all the requirements that one might wish from an ontology inferencing language, nor do we believe that the axiom types we mention exhaust all relevant types. Rather we believe that our experiences in particular domains will push for further categorizations of axioms, further translation mechanisms, and, hence, further extensions of the core RDF(S) representation. All that will have to be agreed upon by communities that want to engineer and exchange ontologies with interesting axioms across particularities of inference engines. Our main objective is to acquaint the reader with our *principle methodology* that is transportable to other translation approaches, inferencing systems, and other axiom types, when need arises.

3.2 Axioms for a relational algebra

The axiom types that we have shown above are listed such that easier axioms come first and harder ones appear further down in the list. Axiom specifications that are referred to as "axioms for a relational algebra" rank among the simplest ones. They describe axioms with rather local effects, because their implications only affect one or two relations. We here show one simple example of these in order to explain the basic approach and some syntax. The principle approach easily transfers to all axiom types from 1.(a)-(g) to 5.

Let us consider an example for symmetry. A common denotation for the symmetry of a relation MARRIEDWITH (such as used for "William is married with Susan') in first-order predicate logic boils down to:

(1) $\forall X, Y \ \ \textsc{marriedWith}(X, Y) \leftarrow \textsc{marriedWith}(Y, X).$

In F-Logic, this would be a valid axiom specification, too. Most often, however, modelers that use F-Logic take advantage of the object-oriented syntax. Concept definitions in F-Logic for *Person* having an attribute MARRIEDWITH and *Man* being a subconcept of *Person* is given in (2), while a fact that William is a *Man* who is MARRIEDWITH Susan appears like in (3).

(2) $\mathit{Person}[\textsc{marriedWith} \Rightarrow\!\!\!\!\Rightarrow \mathit{Person}].$
$\mathit{Man}::\mathit{Person}.$

(3) $\text{William}:\mathit{Man}[\textsc{marriedWith} \twoheadrightarrow \text{Susan}].$

Hence, a rule corresponding to (1) is given by (4).

(4) $\forall X, Y \ \ Y[\textsc{marriedWith} \twoheadrightarrow X] \leftarrow X[\textsc{marriedWith} \twoheadrightarrow Y].$

We denote symmetry as a predicate that holds for particular relations:

(5) $\textsc{Symmetric}(\textsc{marriedWith}).$

In RDF(S), this specification may easily be realized by a newly agreed upon class `o:Symmetric`:

(6) `<o:Symmetric rdf:ID="marriedWith"/>`

For a particular language like F-Logic, one may then derive the implications of symmetry by a general rule and, thus, ground the meaning of the predicate SYMMETRIC in a particular target system. The corresponding transformation rule (here in F-Logic) states that if for all symmetric relations R and object instances X and Y it holds that X is related to Y via R, then Y is also related to X via R.

(7) $\forall R, X, Y \ \ Y[R \twoheadrightarrow X] \leftarrow \textsc{symmetric}(R) \texttt{ and } X[R \twoheadrightarrow Y].$

[7] The reader may note that we have chosen names to coincide with many conventional names, e.g. "symmetry" of relations.

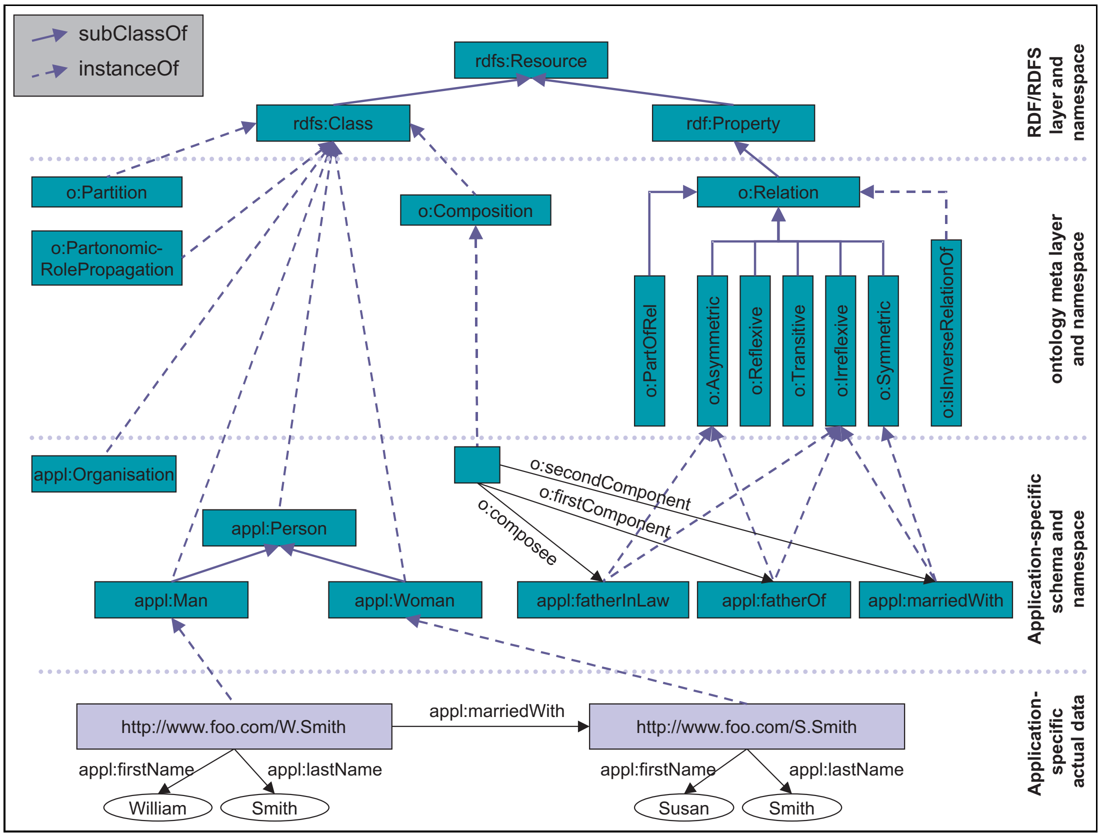

Fig. 3. An Object Model and an Instantiation in RDF(S)

This small example already shows three advantages. First, the axiom specification (6) is rather target-system independent. Second, it is easily realizable in RDF(S). Third, our approach for denoting symmetry is much sparser than its initital counterpart (4), because (7) is implicitly assumed as the agreed semantics for our schema definition.

Following our strategy sketched in the previous subsection, these steps from RDF representation to axiom meaning are now summarized in Table 1. For easier understanding, we will reuse this table layout also in the following subsection.

3.3 Composition of relations

The next example concerns composition of relations. For instance, if a first person is FATHEROF a second person who is MARRIEDWITH a third person then one may assert that the first person is the FATHERINLAWOF the third person. Again different inferencing systems may require completely different realizations of such an implication. The object description of such an axiom may easily be denoted in F-Logic or in RDF(S) (cf. Table 2). The transformation rule works very similarly as the transformation rule for symmetry.

3.4 General axioms

Our approach of axiom categorization is not suited to cover every single axiom specification one may think of. Hence, we still must allow for axioms that are specified in a particular language like first-order predicate logic and we must allow for their representation in RDF(S). There are principally two ways to approach this problem. First, one may conceive a new RDF(S) representation format that is dedicated to a particular inferencing system for reading and performing inferences. This is the way that has been choosen for OIL [9], which has a RDF(S) style representation for a very simple description logics, or Metalog [14], which represents Horn clauses in RDF(S) format.

The alternative is to fall back to a representation that is even more application specific, viz. the encoding of ontological axioms in pure text, or “CDATA” in RDF speak (cf. the example below). In fact, the latter is a very practical choice for many application-specific axioms — once you make very deep assumptions about a particular representation, you are also free to use whatever format you like.

```
<o:GeneralAxiom rdf:ID="WhoPaidForTheWeddingParty">
 <o:text lang="flogic">
   <![CDATA[
       FORALL w, x, y, z
        w:Wedding[groom->x,bride->y,billTo->z] <-
        z[fatherInLawOf->x:Man] AND
        x[marriedWith->y].
   ]]>
 </o:text>
</o:GeneralAxiom>
```

Offering such a distinguished place for arbitrary axioms allows (i) round tripping of ontologies through different ap-

A	<o:Symmetric rdf:ID="marriedWith"/>	RDF(S)
B	$\textsc{Symmetric}(\textsc{marriedWith})$	F-Logic Predicate
C	$\forall R, X, Y \;\; Y[R \twoheadrightarrow X] \leftarrow \textsc{Symmetric}(R)$ and $X[R \twoheadrightarrow Y]$.	Translation Axiom
D	$\forall X, Y \;\; X[\textsc{marriedWith} \twoheadrightarrow Y] \leftarrow Y[\textsc{marriedWith} \twoheadrightarrow X]$.	Target Axiom

Table 1. Symmetry

A	<o:Composition rdf:ID="FatherInLawComp"> <o:composee rdf:Resource="fatherInLawOf"/> <o:firstComponent rdf:Resource="fatherOf"/> <o:secondComponent rdf:Resource="marriedWith"/> </o:Composition>
B	$\textsc{Composition}(\textsc{fatherInLawOf}, \textsc{fatherOf}, \textsc{marriedWith})$
C	$\forall R, Q, S, X, Y, Z \;\; X[S \twoheadrightarrow Z] \leftarrow$ $\textsc{Composition}(S, R, Q) \wedge X[R \twoheadrightarrow Y]$ and $Y[Q \twoheadrightarrow Z]$.
D	$\forall X, Y, Z \;\; X[\textsc{fatherInLawOf} \twoheadrightarrow Z] \leftarrow$ $X[\textsc{fatherOf} \twoheadrightarrow Y]$ and $Y[\textsc{marriedWith} \twoheadrightarrow Z]$.

Table 2. Composition

plications, that (ii) can benefit as much as possible of these portions of the ontology that are undigestible for others.

4 Related Work

The proposal described in this paper is based on several related approaches, viz. we have built on considerations made for the RDF inference service SiLRi [4], the ontology engineering environments ODE [1] and Protégé [6], the ontology interchange language OIL [9], considerations made by Gruber [7], and our own earlier work on general ontology engineering [13, 15].

SiLRi [4] was one of the first approaches to propose inferencing facilities for RDF. It provides most of the basic inferencing functions one wants to have in RDF and, hence, has provided a good start for many RDF applications. In fact, it even allows to use axioms, but these axioms may not be denoted in RDF, but only directly in F-Logic. It lacks capabilities for axiom representation in RDF(S) that our proposal provides.

In our earlier proposals [13, 15] we have discussed how to push the engineering of ontological axioms from the *symbol level* onto the *knowledge level* — following and extending the general arguments made for ODE [1] and Ontolingua [5]. This strategy has helped us here in providing an RDF(S) object representation for a number of different axiom types.

Nearest to our actual RDF(S)-based ontology engineering tool is Protégé [6], which provides comprehensive support for editing RDFS and RDF. Nevertheless, Protégé currently lacks any support for axiom modeling and inferencing — though our approach may be very easy to transfer to Protégé, too.

A purpose similar to our general goal of representing ontologies in RDF(S) is pursued with OIL [9]. Actually, OIL constitutes an instantiation of our methodological approach, as the definition of concepts and relations in description logics is equivalent to the instantiation of a small number of axiom schemata in a particular logical framework. The axiom categorisation we presented in this paper can be effortlessly combined with the ontological meta-layer proposed in OIL. Thus, applications can utilize two vocabularies that complement each other to model classes in a DL-style while at the same time defining axioms on the conceptual level.

Finally, there are other approaches for ontology exchange and representation in XML formats that we do not want to elaborate here, as they fail our litmus test for supporting the RDF(S) metadata standard, e.g. [14, 10].

5 Discussion

We have presented a new approach towards engineering ontologies extending the general arguments made for ODE [1] and Ontolingua [5] in the web formats, RDF and RDFS. Our objectives aim at the usage of existing inferencing services such as provided by deductive database mechanisms [4] or description logics systems [8]. We reach these objectives through a *methodology* that classifies axioms into axiom types according to their *semantic meaning*. Each type receives an object representation that abstracts from scoping issues and is easily representable in RDF(S). Axiom descriptions only keep references to concepts and relations necessary to distinguish one particular axiom of one type from another one of the same type. When the limits of object representations in RDF(S) are reached, we fall back onto target system-specific representations. These may be formulated in RDF versions of languages like OIL or MetaLog — but since they are commonly very specific for particular applications, they may also be expressed by strings (CDATA), the particular semantics of which is only defined in the corresponding application.

Our proposed extension of RDF(S) has been made with a clear goal in mind — the complete retention of the expressibility and semantics of RDF(S) for the representation of ontologies. This includes the relationship between ontologies and instances, both represented in RDF(S). Especially, the notion of *consistency* (cf. [2]) between an RDF model and a schema also holds for ontologies expressed in RDF(S). The integration of the newly defined resources has been carried out in a such a way that all RDF processors capable of processing RDF schemas can correctly interpret RDF models following the ontology schema, even if they do not *understand* the semantics of the resources in the o-namespace.

Special applications like OntoEdit [13] can interpret the o-namespace correctly and thus fully benefit from the richer modelling primitives, if the RDF model is valid[8] according to the defined ontology schema. Our approach has been partially implemented in our ontology engineering environment, OntoEdit. The object-model engineering capabilities for RDF(S) are ready to use, while different views for axiom representations are currently under construction.

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[8] Cf. the "Validator" section in `http://www.ics.forth.gr/proj/isst/RDF/` for a set of operations to check for validity

A The RDF schema for categories of relationships

```
<?xml version='1.0' encoding='ISO-8859-1'?>
<rdf:RDF
  xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
  xmlns:rdfs="http://www.w3.org/TR/1999/PR-rdf-schema-19990303#">

<rdfs:Class ID="Relation">
 <rdfs:subClassOf rdf:resource="http://www.w3.org/1999/02/22-rdf-syntax-ns#Property"/>
</rdfs:Class>

<rdfs:Class ID="Asymmetric">
 <rdfs:subClassOf rdf:resource="#Relation"/>
</rdfs:Class>

<rdfs:Class ID="Reflexive">
 <rdfs:subClassOf rdf:resource="#Relation"/>
</rdfs:Class>

<rdfs:Class ID="Transitive">
 <rdfs:subClassOf rdf:resource="#Relation"/>
</rdfs:Class>

<rdfs:Class ID="Irreflixive">
 <rdfs:subClassOf rdf:resource="#Relation"/>
</rdfs:Class>

<rdfs:Class ID="Symmetric">
 <rdfs:subClassOf rdf:resource="#Relation"/>
</rdfs:Class>

<rdfs:Class ID="PartOfRel">
 <rdfs:subClassOf rdf:resource="#Relation"/>
</rdfs:Class>

<rdf:Description ID="isInverseRelationOf">
 <rdf:type rdf:resource="#Relation"/>
</rdf:Description>

<!-- Definitions for COMPOSITION -->

<rdfs:Class ID="Composition"/>

<rdf:Property ID="composee">
 <rdfs:domain rdf:resource="#Composition"/>
 <rdfs:range rdf:resource="http://www.w3.org/1999/02/22-rdf-syntax-ns#Property"/>
</rdf:Property>

<rdf:Property ID="firstComponent">
 <rdfs:domain rdf:resource="#Composition"/>
 <rdfs:range rdf:resource="http://www.w3.org/1999/02/22-rdf-syntax-ns#Property"/>
</rdf:Property>

<rdfs:Property ID="secondComponent">
 <rdfs:domain rdf:resource="#Composition"/>
 <rdfs:range rdf:resource="http://www.w3.org/1999/02/22-rdf-syntax-ns#Property"/>
</rdfs:Property>

<!-- Definitions for PARTITION -->

<rdfs:Class ID="Partition"/>

<rdfs:Property ID="partitionee">
 <rdfs:domain rdf:resource="#Partition"/>
 <rdfs:range rdf:resource="http://www.w3.org/1999/02/22-rdf-syntax-ns#Property"/>
</rdfs:Property>

<rdfs:Property ID="parts">
 <rdfs:domain rdf:resource="#Partition"/>
 <rdfs:range rdf:resource="http://www.w3.org/1999/02/22-rdf-syntax-ns#Bag"/>
</rdfs:Property>

<!-- Definitions for General Axioms-->

<rdfs:Class ID="GeneralAxiom">
 <rdfs:subClassOf rdf:resource="http://www.w3.org/TR/1999/PR-rdf-schema-19990303#Resource">
</rdfs:Class>

<rdf:Property ID="lang">
 <rdfs:domain rdf:resource="GeneralAxiom"/>
 <rdfs:range rdf:resource="http://www.w3.org/TR/xmlschema-2/#string"/>
</rdf:Property>

<rdf:Property ID="text">
 <rdfs:domain rdf:resource="GeneralAxiom"/>
 <rdfs:range rdf:resource="http://www.w3.org/TR/xmlschema-2/#string"/>
</rdf:Property>

</rdf:RDF>
```