Processing OWL2 ontologies using Thea: An application of logic programming

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Abstract. Traditional object-oriented programming languages can be difficult to use when working with ontologies, leading to the creation of domain-specific languages designed specifically for ontology processing. Prolog, with its logic-based, declarative semantics offers many advantages as a host programming language for querying and processing OWL2 ontologies. The SWI-Prolog **semweb** library provides some support for OWL but until now there has been a lack of any library providing direct and comprehensive support for OWL2.
We have developed Thea, a library based directly on the OWL2 functional-style syntax, allowing storage and manipulation of axioms as a Prolog database. Thea can translate ontologies to Description Logic programs but the emphasis is on using Prolog as an application programming and processing language rather than a reasoning engine. Thea offers the ability to seamless connect to the java OWL API and OWLLink servers. Thea also includes support for SWRL.
In this paper we provide examples of using Thea for processing ontologies, and compare the results to alternative methods. Thea is available from GitHub: http://github.com/vangelisv/thea

1 Motivation

The OWL2 language provides a large variety of powerful constructs for building and reasoning over ontologies. These ontologies are typically developed using sophisticated editing environments by domain specialists rather than computer scientists or programmers. However, there is frequently a need to access ontologies or knowledge bases programmatically - in order to perform scripting operations or to build applications. One popular approach is to use RDF toolchains, which provide access at the triple level. There are a variety of such tools for a variety of programming languages. This approach works well for lightly axiomatized linked-data collections, but for working with the TBoxes of heavily axiomatized OWL2 ontologies the triple view can be too low level.

The OWL API[5] is an example of an alternative approach in which the programmer works directly with OWL2 constructs from an axiom-oriented perspective. The API closely follows the OWL specification, making it a natural fit for working with the TBox of complex ontologies. The OWL API is implemented in Java, the language of choice for many enterprise applications. However, there is something of an impedance mismatch between object-oriented (OO) languages and logical axioms (similar to the well-known impedance mismatch between

OO and relational databases). This has motivated the development of domain-specific languages (DSLs)[9] for manipulating ontologies, including the Ontology Pre-Processing Language (OPPL)[2].

However, the creation of a DSL is an onerous task, and it can be difficult to get the balance between expressivity and simplicity correct. An alternative approach is to use an existing high-level declarative language. Ideally this language should be Turing-complete, and should offer pattern-matching and querying capabilities. Here we explore the use of Prolog as one such language.

2 Prolog as an Ontology Processing Language

Prolog offers many advantages as a host programming language for working with ontologies, due to it's declarative features and pattern-matching styles of programming[1].

A Prolog program is a collection of *horn clauses*, rules of the form **Head :- Body**, where **Head** is a single goal and **Body** consists of a number of sub-goals joined by conjunctions or disjunctions (written "**,**" or "**;**" respectively) . A clause with an empty body is known as a *fact*. A collection of facts is called a *database*. Each goal is a predicate combined with zero or more arguments, where the arguments can be variables (which are written using a leading upper-case character), atoms or compound terms. Prolog predicates are denoted **Predicate/Arity**, where Arity is the number of arguments taken by the predicate. Prolog programs make the closed world assumption and implement *not* using negation-as-failure.

Prolog goals are typically resolved by chronological backtracking (although other resolution strategies are possible). Prolog offers impure non-logical features such as the *cut* predicate to prune the search tree, and meta-logical predicates for performing aggregate operations such as finding all solutions to a goal.

Prolog belongs to a family of rule-oriented languages which have been explored as an alternative basis for the semantic web and reasoning, an approach that has been criticised by some in the OWL community[7]. However, here we are more concerned with Prolog as a *programming* language for working with ontologies rather than a direct substrate for ontologies with logic programming semantics.

There are a number of different Prolog implementations. When considering a system for performing programmatic tasks on ontologies certain considerations such as supporting libraries are important. The SWI-Prolog environment[18] has the advantage of providing both RDF/XML parsers and an efficient in-memory triplestore in the form of the **semweb** library[19].

3 Thea: a library for OWL2

3.1 Design Decisions

Our goal was to build a programming library that supports OWL2 directly through the Prolog database, rather than indirectly via RDF triples. This was

the approach taken by the first version of Thea, developed in 2005 to support OWL as a complement to the SWI-Prolog **semweb** library.

This first version took a *frame-oriented* approach, providing a small number of predicates to support the basic entities - classes, properties and individuals. In redesigning Thea to support OWL2 we decided to opt for an *axiom-oriented* approach, and in particular to follow the OWL2 structural syntax[11] specification precisely. Here, every axiom in the ontology would correspond on a one-to-one basis with facts in the Prolog database.

3.2 Model

Our model directly corresponds to the OWL2 structural syntax[11] specification, with only minor variations between the two. For example, a simple subclass axiom between two named classes (Human and Mammal) is written using a **subClassOf/2** fact:

```
subClassOf('http://example.org#Human','http://example.org#Mammal').
```

In contrast to many programming languages, there is no need for an extensive API for interrogating these structures, as we can directly query the Prolog database using goals with variables as arguments. For example, to find all asserted superclasses of Human we would use a variable in the second argument position:

```
?- subClassOf('http://example.org#Human',X).
```

The system returns with:

```
X = 'http://example.org#Mammal'
```

This is a query over the facts in the asserted database and not a request to a reasoning engine to find all entailed subclasses.

In the cases where arguments are not named entities, we use Prolog terms corresponding to expressions, again with a direct correspondence between the OWL2 specification and Prolog functors and arguments. See table 1 for a comparison of an axiom stated using both OWL2 structural syntax and in the native Prolog form[1].

Thea2 also allows an optional alternate style called *plsyn*, taking advantage of the ability to define infix operators in Prolog syntax, yielding something similar to Manchester syntax[6] yet native Prolog terms (see table 1).

Thea also allows for ontology interrogation using strongly-typed predicates such as **subOjectPropertyOf/2** and **subDataPropertyOf/2**. These are implemented as Prolog rules.

Thea has support for the Semantic Web Rule Language (SWRL). SWRL antecedent-consequent rules are represented in the Prolog database as facts using a two-argument **implies/2** predicate, rather than directly as Prolog rules.

[1] From here on full length IRIs are truncated for brevity. See the documentation in the distribution for a full discussion of namespaces

OWL2	`EquivalentClasses(`
	`  forebrain_neuron`
	`  intersectionOf(neuron`
	`  someValuesFrom(partOf forebrain)))`

Prolog	`equivalentClasses(`
	`  [ forebrain_neuron,`
	`  intersectionOf([ neuron,`
	`  someValuesFrom(partOf, forebrain) ]) ]).`

Plsyn	`forebrain_neuron == neuron and partOf some forebrain.`

Table 1. Comparison of the representation of an OWL axiom in both OWL2 structural syntax and the native form asserted in the Prolog database. Note the minor difference in that where the OWL2 spec allows n-ary predicates to represent sets or lists of entities, we use explicit Prolog list syntax (denoted by the square brackets). We also show a more compact Prolog representation taking advantage of the ability to declare some predicates as infix in Prolog.

3.3 Concrete Representations: Parsing and Serialization

The OWL2 language has a number of alternative concrete forms, the normative one being RDF/XML, which can be parsed and serialized using the SWI-Prolog semweb library. Thea includes Prolog rules for translating between these RDF graphs and the axiom-oriented representation; these rules are based directly on the OWL2 RDF Mapping[3]. There are also parsers and serializers for SWRL and OWL2-XML[10].

Thea also provides a convenient and efficient native prolog representation, in which the ontology is written to or read directly as prolog facts. This can be compiled to an even more efficient binary representation.

3.4 Reasoning

With Thea it is possible to reason using either Logic Programming techniques, or by bridging to external reasoners. Standard prolog queries operate on the asserted axiom database, and the **entailed/1** predicate is used to interrogate the reasoned database.

Description Logic Programs The primary motivation for using Prolog is the declarative programmatic style rather than an alternative fragment of first order logic. However, certain logic programming engines offer useful reasoning capabilities that complement description logic reasoning.

Thea is able to write a combination of OWL2 ontologies and SWRL rules to Description Logic Programs (DLP)[4]. We extended the standard translation, defined for OWL1 to include property chain axioms and SWRL. The resulting logic programs can be evaluated by Prolog implementations that offer tabling [15], such as XSB, Yap or B-Prolog.

Backward-chaining Standard Prolog engines use backward chaining with backtracking to evaluate goals (known as SLD resolution). Backtracking can be used to traverse subclass hierarchies and property chains, provided there are no cycles, as this would lead to non-termination.

External reasoners Thea also includes as an optional component a bridge to the OWL API using the SWI JPL package. This allows seamless access to the extensive capabilities of the OWL API, including access to powerful DL reasoners such as Pellet[16] and FaCT++[17].

Thea also implements the OWLLink interface, which allows access to different reasoners[8].

4 Applications of Logic Programming to Ontologies

The use of high level declarative programming languages can be advantageous when working with rich and complex ontology models. Here we present some examples of using Prolog plus Thea to perform different tasks.

4.1 Ontology Querying

As noted previously, there is no specific API for interrogating or manipulating OWL2 ontologies using Thea2. The declarative pattern matching and symbol manipulation features of Prolog suffice. In addition it is simple to create new rules, effectively naming queries.

For example, we can define a predicate for determining the least common ancestor (LCA) over the SubClassOf axiom:

```
common_ancestor(X,Y,A) :-
  entailed(subClassOf(X,A)), entailed(subClassOf(Y,A)).

least_common_ancestor(X,Y,A) :-
  common_ancestor(X,Y,A),
  \+ ((common_ancestor(X,Y,A2), A2\=A,
       entailed(subClassOf(A2,A)))).
```

The **least_common_ancestor/3** predicate can then be re-used in subsequent queries.

Another powerful feature of Prolog is the ability to perform meta-logical queries involving aggregation. For example, if we want to summarise all classes

by the number of instances asserted to be types of that class we can do this using **aggregate/4**:

```
class(C),aggregate(count,I,classAssertion(C,I),Num).
```

This goal would succeed once for every class **C**, unifying **Num** with the number of individuals in class **C**.

By combining the LCA predicate with aggregate queries it becomes very simple to write *semantic similarity* applications, a popular use of biological ontologies[14]. The Thea distribution includes a sample application for calculating semantic similarity between individuals in OWL knowledge bases based on the information content of classes in common.

4.2 Ontology Processing

Ontologies are typically created and maintained using development environments such as Protege[13], which provide a graphical user interface to allow domain experts to view, create and edit axioms. In addition to these end-user oriented tools, there is frequently a need to do programmatic processing or scripting of ontologies for tasks that would be tedious and repetitive to do by hand.

Consider a hypothetical ontology that by default follows a strict jointly-exhaustive pairwise-disjoint paradigm, but with occasional exceptions that are explicitly declared using a specified annotation property. We can automate the generation of these axioms using the following goal, which can be evaluated in a failure-driven loop:

```
class(Y),
setof(X,(subClassOf(X,Y),
         \+ annotationAssertion(status,X,unvetted)),
      Xs),
assert_axiom(disjointUnion(Y,Xs))
```

Of course it is possible to write a program to do this in a language such as java using the OWL API, which may be preferable in many circumstances. However, if there is a need to perform multiple scripting tasks on an ad-hoc basis then a declarative means of processing ontologies can be a useful complementary technique.

The examples directory in the Thea distibution contains many recipes such as this one.

4.3 Label generation

One of the challenges in ontology development is maintaining consistent class labels that are intuitive to the targeted community of users. Given the appropriate equivalence axioms it should be possible to auto-generate labels or suggestions for labels.

For example, given a class expression **length and qualityOf some (axon and partOf some pyramidal_neuron)** we might want to generate a more concise user-friendly label such as *length of pyramidal neuron axon*. This label contains less information than the class expression, but is unambiguous enough as a label intended for a domain expert. We might also want to generate alternate labels for composite classes based on alternate labels of the composing classes.

Prolog Definite Clause Grammars (DCGs) allow for simple configuration of community-specific class labeling rules using production rules such as the following, which uses the preposition "of" in place of the more verbose ObjectProperty:

```
term(Q and qualityOf some A) --> quality(Q),[of],anatomical(A).
```

The same grammars can be used to parse controlled natural language expressions. This technique has been used for both parsing and label generation in many biological ontologies using Obol grammars[12].

The Thea distribution comes with some example grammars.

4.4 Translating to and from other sources

Ontologies can be constructed both manually and automatically. In the latter case, the ontology may be constructed from some other data sources: flat files, XML or relational data.

The pattern matching and rule-driven nature of Prolog make it a good match for data translation tasks.

To take a biological example, given a two-column table mapping types of cell to the markers expressed on the surface of that cell, we can specify the translation to a complex OWL axiom using a single rule:

```
CellType < hasPart some (surface and hasPart some Marker) :-
    cell_marker(CellType,Marker).
```

Many Prolog implementations also provide libraries for XML processing and for database connectivity, which means that similar declarative rules such as the above can be specified for these sources too. The Thea distribution includes examples of both.

4.5 Ontology Web Applications and Web Services

In addition to providing an expressive means of querying, processing and performing translations on ontologies, it is possible to write full blown applications using Thea2 via the SWI-Prolog http library. The Thea distribution contains some simple examples, including a basic web-based axiom browser.

5 Comparison with other systems

5.1 SPARQL

The SPARQL language is commonly used for querying ontology-centric linked data, and sometimes for querying the ontology itself (TBox querying). Thus there is some overlap with the querying capabilities of Prolog+Thea. However, SPARQL suffers from certain limitations in certain circumstances:

- No means of updating data
- Too RDF-centric for querying complex TBoxes
- Lack of ability to name queries (as in relational views)
- Lack of aggregate queries
- Lack of programmability

There are various extensions to overcome these limitations: SPARUL for updates, SPARQL-DL for OWL-level querying of TBoxes (there is now a W3C working group formed to add other missing features in SPARQL). In addition SPARQL enjoys the distinction of being a W3C standard and is supported by most triplestores, and SPARQL engines may also provide efficient query optimization. Nevertheless, sometimes SPARQL does not offer the requisite features to perform certain kinds of queries or translations, such as the ones described in this paper. In these cases the ability to perform queries via Prolog offers a useful complementary tool in the semantic web developers arsenal.

5.2 OPPL

Another means of processing ontologies is using OPPL, a Domain Specific Language designed specifically for this task. Table 2 shows an OPPL example for asserted that all subclasses of gender are disjoint, together with the equivalent Prolog:

OPPL	Thea

`?x:CLASS, ?y:CLASS`
`SELECT ?x subClassOf gender,`
`?y subClassOf gender`
`WHERE ?x!=?y`
`BEGIN`
`ADD ?x disjointWith ?y`
`END;`
	`subClassOf(X,gender),`
	`subClassOf(Y,gender),`
	`X\=Y,`
	`assert_axiom(disjointClasses([X,Y]))`

Table 2. Comparison of ontology processing in OPPL versus a failure-driven prolog loop using Thea. This example is taken from the OPPL online documentation

In this case we can see a close correspondence, with minor syntactic differences. OPPL is perhaps easier to teach, being smaller, and having a familiar SQL-like syntax. OPPL also has the significant practical advantage of currently being integrated with the Protege 4 environment.

However, Prolog offers many advantages such as higher expressivity, Turing completeness, named queries, meta-logical predicates and well-understood semantics. Although we are not aware of a full formal specification of OPPL, it appears from the grammar that there are many examples presented in this document (e.g. the one in section 4.2) that would require some kind of extension to OPPL.

5.3 The OWL API

The most fully featured programmatic interface to OWL2 is the Java OWL API. Of course, Thea offers considerably less capabilities, and in addition the OWL API is a better choice for many software developers, being implemented in Java. However, we believe that for a certain subset of tasks, the declarative nature of Prolog offers a number of advantages.

An alternative strategy is to use the OWL API in conjunction with a more declarative JVM language. This is the approach taken by the Lisp Semantic Web (LSW) library[2], which runs on the JVM. In fact Thea also provides a bridge to the OWL API, although this is optional, and the user can work directly with axioms expressed natively in a Prolog database.

Benchmarks show that the performance of Thea is comparable with the OWL API[3].

6 Conclusions

Thea offers support for OWL2 within a Prolog environment. The full structural syntax is supported. Thea can be used to simplify many programmatic tasks associated with ontologies, including ontology querying and processing. In addition, Thea can be used to construct full applications that have dependencies on complex ontologies.

Thea is available from GitHub (http://github.com/vangelisv/thea) and from the Thea website (http://www.semanticweb.gr/thea). At this time use of the full library requires SWI-Prolog, although we hope to soon offer full support for Yap Prolog. A subset of features (excluding RDF/XML reading and writing) are available to any ISO-compliant Prolog implementatin

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