AN EXPERIMENT ON THE CONNECTION BETWEEN THE DESCRIPTION LOGICS’ FAMILY $\mathcal{DL}<\forall^T_0>$ AND THE REAL WORLD

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Abstract

This paper describes the analysis of a selected testbed of Semantic Web ontologies, by a SPARQL query, which determines those ontologies that can be related to the description logic $\mathcal{DL}<\forall^T_0>$, introduced in [4] and studied in [9]. We will see that a reasonable number of them is expressible within such computationally efficient language. We expect that, in a long-term view, a temporalization of description logics, and consequently, of OWL(2), can open new perspectives for the inclusion in this language of a greater number of ontologies of the testbed and, hopefully, of the “real world”.

INTRODUCTION

In the last years, Semantic Web has increasingly expanded its area of influence. Being an innovative instrument for the retrieval of not expressly stored information and a way of organizing concepts and relations by their meaning, it broadens up plenty of horizons for knowledge representation. Though, only a bunch of experts and researchers know that under a surprisingly vast dimension of new features there lies a mathematical and logical structure inside which they fight day by day for the balancing of expressiveness and efficiency. The Description Logics formalisms, which we will see in Section 1, are the formal bases for the so-called Web 3.0, that should allow one to automatically infer (and retrieve) new information from reasoning on “sematicized” knowledge repositories. Some examples of families of logics are described in the following, together with a short coverage of arguments such as RDF graphs and OWL.

Section 2 introduces the description logic $\mathcal{DL}<\forall^T_0>$, showing notable characteristics of expressive power and polynomial complexity. In the same section, a more detailed description of the analysis, which may be seen as a conceptual experiment, follows. Our purpose is to show that a good number of real-world ontologies may be related to this family of logics. Results are promising enough to spur us to stay on this path and complement it with studies on temporalization of Description Logics and, consequently, of Semantic Web (briefly touched in this report), which we will approach in the near future.

The SPARQL query which was specifically created to assess the membership of some real-world ontologies to the aforementioned logic is reported in Appendix A.

1 THEORETICAL FUNDAMENTALS

1.1 Description Logics

Description Logics (DLs) are a family of formalisms for knowledge representation, built on logic-based semantics. They are founded on some fundamental ideas:

- basic syntactic “blocks” are atomic concepts (1-ary predicates), atomic roles (2-ary predicates) and individuals (costants);
- the expressiveness of a certain language depends on the use of a set of chosen constructors, that give birth to complex concepts and roles starting from existing ones;
- by means of classification of concepts, a subsumption hierarchy is established, which specifies what concept includes or is included by another;
On the assumption that a Knowledge Representation System (KR-System) is to give an answer to a user query, reasoning algorithms for DLs should be regarded as decisional procedures which return a positive or negative verdict. This raises the decision problem for such languages. Furthermore, having an answer does not always mean getting it in a reasonable lapse of time, and that compels us to consider also the complexity of algorithms at stake. Decidability and complexity directly depend on the expressive power of the description logic we use: whereas very expressive DLs tend to have inference problems and be computationally hard (or even undecidable), the DLs that are more efficient in reasoning turn out to be not expressive enough to represent all concepts and relations in the domain of interest. Research still going on in the field of DLs just aims at the ability of balancing expressiveness against efficiency, while not dropping semantic precision that could make it applicable to real world situations.

A Description Logics Knowledge Base (DLKB) is made of two components: TBox (Terminological Box) and ABox (Assertional Box). The former contains the vocabulary, i.e., the definitions of atomic and non-atomic concepts and roles, called axioms, whereas the latter describes individuals in terms of this vocabulary, i.e., it includes the declarations, called assertions, of their instances. By means of the TBox we can name complex descriptions of concepts and roles. The language for such a naming is what distinguishes one DL from another and is based on a model-theoretic semantics. Thus statements in TBox and ABox can be regarded as first-order logic formulas. Reasoning procedures for the terminological part are used to verify the satisfiability of a description (i.e., its non-contraditoriness), or whether it may be subsumed by another (i.e., whether the latter is more general than the former), while those for the assertive part establish whether its set of assertion is consistent (i.e., it has a model or it entails that a certain individual is an instance of a given concept). Satisfiability tests for descriptions and consistency tests for a set of assertion allow one to establish whether the knowledge base is meaningful or not, whereas subsumption tests allow one to maintain a hierarchy of concepts ab universalis; finally, instance tests give one the ability of querying the system against single individuals.

More formally, a generic DL axiom is a formula of one of the following types:

- \( C \equiv D \) (equivalence between concepts)
- \( C \subseteq D \) (subsumption between concepts)
- \( R \equiv S \) (equivalence between roles)
- \( R \subseteq S \) (subsumption between roles),

where the symbols \( C, D \) are names or expressions of complex concepts, which are formed by 1-ary or 2-ary operations on/between atomic (indicated by \( A \) in the following) or complex concepts, while \( R, S \) are names or expressions of complex roles which are formed by 1-ary or 2-ary operations on/between atomic (indicated by \( P \) in the following) or complex roles.

A generic DL assertion is a formula of one of the following types:

- \( C(a) \) (concept assertion)
- \( R(a, b) \) (role assertion),

where the symbols \( a, b \) are names of individuals, for which the concept \( C \) or the role \( R \) holds.

From a semantical point of view, an interpretation \( \mathcal{I} \) is a pair \( (\Delta^\mathcal{I}, \mathcal{I}) \), where the non-empty set \( \Delta^\mathcal{I} \) represents the domain of the interpretation and the interpretation function \( \mathcal{I} \) associates to every atomic concept \( A \), a relation \( P^\mathcal{I} \subseteq \Delta^\mathcal{I} \times \Delta^\mathcal{I} \) to every atomic role \( P \), and an element \( a^\mathcal{I} \in \Delta^\mathcal{I} \) to every individual \( a \). We write:

- \( \mathcal{I} \models (C \equiv D) \) iff \( C^\mathcal{I} = D^\mathcal{I} \)
- \( \mathcal{I} \models (C \subseteq D) \) iff \( C^\mathcal{I} \subseteq D^\mathcal{I} \)
- \( \mathcal{I} \models (R \equiv S) \) iff \( R^\mathcal{I} = S^\mathcal{I} \)
- \( \mathcal{I} \models (R \subseteq S) \) iff \( R^\mathcal{I} \subseteq S^\mathcal{I} \)

1. The equivalence and subsumption between roles may be indicated also by the symbols \( = \) and \( \subseteq \), respectively.
2. A large number of constructs is listed in the table at the end of this section.
3. In the following, \( \mathcal{I} \models \phi \) means \( \mathcal{I} \) satisfies \( \phi \), where \( \phi \) can be an axiom or an assertion. A syntax/semantical reference for the main axioms, assertions and property declarations is listed in the table at the end of this section.
4. "iff" is short for "if and only if".
• $I \models C(a)$ iff $a \in C^I$
• $I \models R(a, b)$ iff $(a, b) \in R^I$

Finally, we say that $I$ is a model for a DLKB $K$ (and write $I \models K$) if $I$ satisfies all the axioms and assertions of $K$. The latter is said to be consistent if there exists at least an interpretation satisfying it, and the search of this interpretation (consistency problem) is just the clue to reasoning.

1.2 Families of logics

As already observed, distinct DLs are characterized by the constructs allowed to form complex concepts and roles starting from atomic ones. The names are usually specified by a series of alphabet letters and symbols. In the following, we will not concentrate on formal semantics, but, for the sake of clarity, we will only hint at the meaning of some constructs.

By way of an example, we briefly describe the $ALC$ logic (Attributive Language with Complements). Its syntax obeys the following rules:

$$C, D \rightarrow A | \top | \bot | \neg C | C \cap D | C \cup D | \forall R.C | \exists R.C,$$

where $\top$ denotes the concept enclosing any other one (top concept), $\bot$ denotes the concept enclosed in any other one (bottom concept), $\neg$ negates a concept; $\cup$ represents the union of concepts (notice the analogy with the corresponding set operators) and $\cap$ represents the intersection of concepts. The last two constructs are called respectively universal and existential restriction, and are pivotal in research connected to this report. The concepts that can be built in $ALC$ are called $ALC$-concepts. The axioms and assertions that may be expressed in the $ALC$ logic are

$$C \equiv D, \quad C \subseteq D, \quad C(a),$$

which indicate, respectively, equivalence and subsumption (also called $GCI$, General Concept Inclusion) between two concepts, and the membership of a concept. However, reasoning in $ALC$ has a PSPACE-complete computational complexity.

In addition to those seen above, the most common constructs for concepts which can be formed in DLs are $\leq 1.R$ (functional restriction, denoted $r$, that is equivalent to $\exists R.\top$), $\leq n R$ and $\geq n R$ (numerical restrictions, $N$, which enclose the functional one), $\leq n R.C$ and $\geq n R.C$ (qualified restrictions, $Q$, that include the numerical ones), $\{a\}$ and $\{a_1, \ldots, a_n\}$ (nominals, $O$), and $\exists R.Self$ (self-concept). Constructs for roles are often denoted by an operator symbol inside brackets after the name of the logic. They are $R^\circ$ (inverse role, $I$), $R \cup S, R \cap S$ and $\neg R$ (role union, intersection and complement, respectively), $R \circ S$ (role composition, also used in chain), $R^+$ (transitive and reflexive-transitive closure of roles), $id(C)$ (concept identity), and $R_C, R_D$ and $R_{C\cup D}$ (role restrictions). Sometimes, the symbols $U$ (or $\forall$, universal role, defining the role which encloses any other one) and $N$ (or $\triangle$, empty role, defining the role enclosed in any other one) are used. Other kinds of axioms which can be introduced are $R \equiv S$ (equivalence between roles), $R \subseteq S$ (hierarchy between roles), $H$, denoted also by $R \subseteq S$, and the relative assertion $R(a, b)$ (role instance). The reflexive, irreflexive, symmetric, antisymmetric, transitive, intransitive, disjunctive (two roles having no pair of elements in common), functional and inverse functional properties for roles are denoted by symbols that often differ in literature, but are never ambiguous, e.g. respectively $Sym(R), Asym(R), Refl(R), Irrefl(R), Tr(R), Intr(R), Disj(R), Fn(R), InvFn(R)$. When transitive property is allowed, we use the symbol $S$, which corresponds to $ALC(*$). Sometimes, even small differences among logics (e.g., limitation on the use of atomic rather than complex roles on the right or left part of an assertion) can make a big difference in expressiveness and complexity. Thus, it is not always easy to concisely denote DLs, that consequently constitute an ever-open research field.

One or more among the above described constructs, axioms and assertions are present in the families of logics that are the base of languages used in ontologies. Among these, an important example is the logic $sROIQ_{(D)}$ (in literature always denoted by $SRQ:D$), at the bottom of the OWL 2 DL profile, which will be discussed in the following (the letter in parenthesis indicates the use of concrete domains, that will not be discussed here). Its syntax is easily inferred from the symbols, while its complexity is $N2EXP\text{-time}$-hard.²

²By the symbol $\cdot$, we mean that a DL allows complex inclusions of the kind $R \subseteq S$ and $R \subseteq S'$.
Syntax | Semantics
--- | ---
\(C \equiv D\) | \(C^2 = D^2\)
\(\neg C\) | \(\neg C^2 = \neg D^2\)
\(\forall a \in C\) | \(a^2 \in C^2\)
\(\exists a \in C\) | \(a^2 \notin C^2\)
\(R \equiv S\) | \(R^2 = S^2\)
\(R \subseteq S\) | \(R^2 \subseteq S^2\)
\(R(a, b)\) | \((a, b)^2 \in R^2\)
\(\neg R(a, b)\) | \((a, b)^2 \notin R^2\)
\(R \cap S = N, \mathsf{Disj}(R, S)\) | \(R^2 \cap S^2 = \emptyset \times \emptyset\)
\(\mathsf{Refl}(R)\) | \((\forall a \in \Delta^2) \{(a, a) \in R^2\}\)
\(\neg \mathsf{Refl}(R)\) | \((\forall a \in \Delta^2) \{(a, a) \notin R^2\}\)
\(\mathsf{Sym}(R)\) | \((\forall (a, b) \in R^2) \{(b, a) \in R^2\}\)
\(\neg \mathsf{Sym}(R)\) | \((\forall (a, b) \in R^2) \{(b, a) \notin R^2\}\)
\(\mathsf{Trans}(R)\) | \((\forall (a, b) \in R^2) \{(b, c) \in R^2 \rightarrow (a, c) \in R^2\}\)
\(\neg \mathsf{Trans}(R)\) | \((\forall (a, b) \in R^2) \{(b, c) \in R^2 \rightarrow (a, c) \notin R^2\}\)

Table 1.2. Main types of axioms and assertions on concepts and roles

1.3 Semantic Web

The so-called Web 2.0 describes the current model of information search. The difference with Web 1.0 is represented by the change in the origin of this information (from below—users—rather than from above—webmasters).

\[\text{Table 1.1. Main constructs for concepts and roles}\]

\[\text{Table 1.2. Main types of axioms and assertions on concepts and roles}\]
Yet, a paradigm change in its fundamental structure has not occurred, as the creator of Web, Tim Berners-Lee, wished instead. Indeed, contents are still exclusively made up of pages connected by links, whose nontrivial words, together with metadata, are indexed by search engines, by means of which a correspondence between those and the one inserted by users can be found. In this way, notwithstanding the high efficiency and precision of the algorithms involved, such engines constitute a “stupid” example of information retrieval, where the matching between terms, even if advanced, weighs more than their meaning.

The change brought by the so-called Semantic Web (SW or Web 3.0) addresses the main issue that in the Web, as we know it, most of the contents are structured in order to be read by humans, rather than investigated by programs in an automatic way. A computer can jump from page to page by following links, but it does not make any assumption on the semantics of their contents. SW is an extension of “previous” Web that allows one to assign a meaning to information and provides machines with the ability to elaborate and “understand” what in the past they could only show. For all this to work, computers should be able to access well-structured information schemas and apply inference rules to permit automatic reasoning, in order to delocalize knowledge representation and spread it over the Net. The languages these rules apply should be expressive enough to make the Web capable of “reasoning” in a versatile and widespread way. That is made possible by tools such as eXtensible Markup Language (XML), Resource Description Framework (RDF) and the ontologies described by the Ontology Web Language (OWL).

1.4 RDF graphs

RDF is a model for representation of information on the Web. The basic idea is that every resource (concept, class, property, object, value, etc.) can be univocally described in terms of simple or identified-by-value properties. All this permits to schematize an RDF model by means of an oriented graph, whose nodes represent primitive objects and whose edges denote properties. The limited vocabulary of RDF is extended by RDFS (RDF Schema), which allows one to define classes and properties in a more powerful way. E.g., it is possible to define a property as a relation by indicating its domain and/or range, or say what class is a subclass of another.

From a data structure point of view, an RDF graph may be seen as a set of triples of type (subject predicate object). For each triple, subject and object are two nodes connected by an edge that represents a predicate; thus, the subject of a triple may be the object of another and viceversa. Each of these nodes may be identified by a URI/IRI, and so it can represent a resource, or it may be simply a “connector” (in this case, it is called a blank node, bnode, or anonymous node). If an object is not a subject of another triple, it may also be a literal, i.e., a datum representing a value in a certain domain.

On the representation side, W3C suggests five types of serializations for an RDF graph, the most used of which are RDF/XML (XML language is used) and Turtle (descriptions through lists of triples). XML is used because of its precise representation of data. Thus, they can be shared, by means of RDF, among various Web applications while preserving their original meaning.

1.5 Ontologies

OWL ontologies extend RDFS vocabulary further. If RDFS guarantees generality and precision in constructing knowledge representation, with OWL we reach such an expressiveness that we can “argue” about described information and “extract” more, through reasoning. It provides powerful tools to define classes (that represent concepts), properties (relations among classes and individuals (their instances), and gives the chance to combine them in logic constraints by means of which necessity and/or sufficiency may be expressed.

Upon a W3C recommendation, OWL is made up of three sublanguages with increasing expressiveness: OWL Lite, OWL DL and OWL Full. The first two have an almost total correspondence between two peculiar DLs (resp. SHIF(D) and SHOIN(D)). The last one uses the same subset of OWL DL constructs, but allows them to be unconstrained, according to RDF style. Due to the lack of restrictions on transitive property and to the possibility of handling concepts as individuals (metamodeling), OWL Full turns out to be undecidable and thus, for the correspondence between that and any of the aforesaid DLs, OWL DL is the most expressive decidable sublanguage of OWL.

OWL 2 extends OWL by enhancing its features and expressiveness. Apart from a limited number of cases, OWL 2 is perfectly “backward compatible” with the old OWL (which we call OWL 1 to differentiate it from the OWL 2), i.e., all the ontologies of the latter keep the same semantics as that they had before, even if “fed” to a reasoner for OWL 2. Concisely, OWL 2 introduces a simplification into the writing of the most common statements, it permits

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7The serialization of an object is the process which allows one to represent it in an accessible way, in our case a text file.
8Computer science ambitiously draw on the philosophical term ontology to show that the OWL language can describe the world starting from its ultimate constituents and from relations among them.
9OWL-Lite and OWL-DL provide the possibility of defining annotations, which correspondent DLs do not do. In any case, annotations affect neither reasoning, nor complexity, nor decidability. For the sake of precision, OWL-Lite is considered a “syntactic subset” of OWL-DL.
10Obviously, nothing excludes there is another decidable and more expressive—but not studied yet—sublanguage.
metamodelling, together with some new constructs which increase its expressiveness, and it extends support to data types.

As for sublanguages, in OWL 2 we can deal with OWL 2 Full and OWL 2 DL. As mentioned before, the latter corresponds to the sROIQ(D) logic. Though the former may be syntactically seen as the union of the latter with RDFS, it is semantically compatible with OWL 2 DL (insofar as its semantics allows one to draw all the inferences that can be drawn by using the semantics of OWL 2 DL). Similarly to the analogue sublanguage OWL 1 Full, OWL 2 finds application in the modelling of concepts where reasoning is not required. A new feature of OWL 2 is the use of profiles (i.e., fragments of language) OWL 2 EL, OWL 2 QL and OWL 2 RL: the first is useful for applications involving ontologies that contain a great number of classes and/or properties; the second aims at those applications with large volumes of instances, where answering the queries is of primary importance (from which the name QL, Query Language); the last profile is useful in applications not requiring the sacrifice of too much expressiveness to efficiency. We will not delve into the structural characteristics of these profiles. Here, we only say that they are grounded on very different DLs, each of them fit for the specific purpose they are designed for.

1.6 Syntactical correspondence of OWL(2) with DLs

As to its practical representation, an ontology is a RDF/XML-structured text file, but, for our goals, it will be more useful to think to it in terms of an RDF graph and, thus, of triples. Table 1.3 describes the correspondence between the most common constructs of DLs and such triples (or a single resource, where applicable), which use RDF(S) syntax together with that of OWL(2). It also contains the names given by OWL to the fundamental concepts and roles of DLs. It is interesting to notice how a DL construct often corresponds to more triples, which sometimes makes interpretation quite hard. The symbols :x and _list in the Table 1.3 indicate respectively a blank node and a list (a structure we will not deal with), whereas the prefixes before the elements of triples represent standard W3C namespaces, which serve as abbreviations for the URIs they refer to.12

1.7 SPARQL

One of the most widespread languages for querying against ontologies is SPARQL (recursive acronym for SPARQL Protocol And RDF Query Language). Although it has lots of analogies with SQL, most of which syntactical, it is equipped with a fundamentally different semantics. As query languages for databases essentially work on tables and handle logic conditions to select the rows of these tables that satisfy them, the WHERE clause in SPARQL finds matches between the triples of the query and those of the ontology indicated in the FROM clause. The logic assessments are relegated to the FILTER operator, which possesses a big expressive power, thanks to its several functions, but is rarely used due to the loss of efficiency that its presence may cause.13 The SELECT clause is very similar to that of SQL. It accepts DISTINCT as a keyword and the classical aggregation operators (COUNT, SUM, MIN, AVG and MAX), while the GROUP BY and HAVING clauses are often used (another similarity) to refine the selection. The involved variables are preceded by the symbol '?', whereas constants do not have a particular syntax, even if they generally coincide with URI/IRIs of resources present in the ontology one is handling.

Analyzing in finer detail the WHERE clause, one can say that the triples to match are enclosed in a block between braces and separated by a dot, which implies their intersection. Inside these braces, more sub-blocks may be found, which are useful in making the union (UNION operator) and the difference (MINUS operator) between sets. The matching is valid if the variables having the same names in the clause have the same values in the ontology. There exist some useful shortening, such as the use of semicolon or colon in place of dot, which act respectively in the following way:

?s ?p1 ?o1 ; ?p2 ?o2 . shortens ?s ?p1 ?o1 . ?s ?p2 ?o2 .
?s ?p ?o1 , ?o2 . shortens ?s ?p ?o1 . ?s ?p ?o2 .

In addition to selection, one can also have the DESCRIBE, ASK and CONSTRUCT query types, which we will not review here. The employment of the PREFIX clauses, that precede the real query and indicate the abbreviations for namespaces used inside of it, is quite peculiar.

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11In this way, OWL 1 Lite, OWL 1 DL and OWL 2 DL may be considered profiles of OWL 2.

12The correspondences between namespaces and prefixes are:
- rdf: http://www.w3.org/1999/02/22-rdf-syntax-ns#
- rdfs: http://www.w3.org/2000/01/rdf-schema#
- owl: http://www.w3.org/2002/07/owl#
- xsd: http://www.w3.org/2001/XMLSchema#

13Depending on implementation, the FROM clause may be implied because software loads in memory the ontology model separately.
| DL construct | RDF(S)/OWL(2) resource/triple(s) |
|-------------|----------------------------------|
| ⊤           | owl:Thing                        |
| ⊥           | owl:Nothing                      |
| C ⊆ D       | (C rdfs:subClassOf D)            |
| C ≡ D       | (C owl:equivalentClass D)        |
| C ∈ ¬D opp. | C ∩ D ⊆ ⊥                       |
|            | (C owl:disjointWith D)           |
|            | (_:x owl:intersectionOf _list(C1, C2, ..., Cn)) |
|            | (_:x owl:unionOf _list(C1, C2, ..., Cn)) |
| ¬C          | (_:x owl:complementOf C)         |
|            | {a1, a2, ..., an}                |
|            | (_:x owl:oneOf _list(a1, a2, ..., an)) |
| ∃RC         | (_:x owl:someValuesFrom C)       |
|            | (_:x owl:onProperty R)           |
| ∀RC         | (_:x owl:allValuesFrom C)        |
|            | (_:x owl:onProperty R)           |
| ≤ nR        | (_:x owl:minCardinality n)       |
| ≥ nR        | (_:x owl:maxCardinality n)       |
| ≤ nR ∩ ≥ nR | (_:x owl:cardinality n)          |
|            | (_:x owl:onProperty R)           |
| ≤ nRC        | (_:x owl:minQualifiedCardinality n) |
|            | (_:x owl:onClass C)              |
| ≥ nRC        | (_:x owl:maxQualifiedCardinality n) |
|            | (_:x owl:onClass C)              |
| ≤ nRC ∩ ≥ nRC | (_:x owl:qualifiedCardinality n) |
|            | (_:x owl:onClass C)              |
|            | (_:x owl:onProperty R)           |
|            | (_:x owl:hasSelf true)           |
| C(a)        | (a rdf:type C)                   |
| {a1} ≡ {a2} | (a1 owl:sameAs a2)               |
| {a1} ⊆ ¬{a2} | (a1 owl:differentFrom a2)        |
| U opp. ∨    | owl:topObjectProperty            |
| N opp. ∆    | owl:bottomObjectProperty         |
| R ⊆ S       | (R owl:subPropertyOf S)          |
| R ≡ S       | (R owl:equivalentProperty S)     |
| R ∩ S ⊆ N   | (R owl:PropertyDisjointWith S)   |
| R ⊑ R1 ◦ R2 ◦ ... ◦ Rn ⊑ R | (R owl:propertyChainAxiom _list(R1, R2, ..., Rn)) |
| Ref(R)      | (R rdf:type owl:ReflexiveProperty) |
| Irref(R)    | (R rdf:type owl:IrreflexiveProperty) |
| Sym(R)      | (R rdf:type owl:SymmetricProperty) |
| Asym(R)     | (R rdf:type owl:AsymmetricProperty) |
| Trans(R)    | (R rdf:type owl:TransitiveProperty) |
| Fn(R)       | (R rdf:type owl:FunctionalProperty) |
| InvFn(R)    | (R rdf:type owl:InverseFunctionalProperty) |
| R(a, b)     | (a property_name b)              |
| ∼R(a, b)    | (∼:x rdf:type owl:NegativePropertyAssertion) |
|            | (_:x owl:sourceIndividual a)     |
|            | (_:x owl:assertionProperty R)    |
|            | (_:x owl:targetIndividual b)     |

Table 1.3. Correspondences between DLs and SW
2 ANALYSIS AND RESULTS

2.1 The family $\mathcal{DL}<\forall_0>$

Description Logics derived from decidable fragments of set theory, generally denoted by the notation $\mathcal{DL}<\text{LANGUAGE\_NAME}>$, are having considerable importance.

The family of logics underlying this class of ontologies, object of research this project is based on, is focused on the fragment $\forall_0$, which has a good expressiveness w.r.t. knowledge representation in real-world applications. The interest aroused by that is related to NP-completeness of its decision procedure in some cases of practical relevance. $\mathcal{DL}<\forall_0>$-concepts and $\mathcal{DL}<\forall_0>$-roles are formed according to the syntax

\[
\begin{align*}
C, D & \to A \mid \top \mid \bot \mid \neg C \mid C \sqcap D \mid C \sqcup D \mid \{ a \} \mid \exists R.\text{Self} \mid \exists R.\{ a \} \\
R, S & \to P \mid U \mid R^\sim \mid \neg R \mid R \sqcap S \mid R \sqcup S \mid R_C \mid R_D \mid R_{CD} \mid \text{id}(C) \mid \text{sym}(R),
\end{align*}
\]

while a $\mathcal{DL}<\forall_0>$-KB is made of axioms and assertions of the following kind:

\[
\begin{align*}
C & \equiv D & C & \subseteq D & C & \sqsubseteq \forall R.D & \exists R.C & \subseteq D & C(a) & R(a, b) \\
R & \equiv S & R & \subseteq S & R \circ R' & \subseteq S & \text{trans}(R) & \text{refl}(R) & \text{asym}(R) & \text{fn}(R) & \text{invfn}(R).
\end{align*}
\]

We may notice that universal restriction is allowed only in the right part of a subsumption, whereas existential restriction can appear only in the left part. In addition, neither numerical, nor qualified restrictions are allowed.

2.2 Description of the experiment

Our analysis is aimed at selecting ontologies corresponding to the $\mathcal{DL}<\forall_0>$ family, in order to use them as a base of study for this family of logics in real-world applications. To do that, it is necessary to query against as many as possible publicly available ontologies in a quick and efficient way. The use of queries in SPARQL conveniently lends itself to the purpose. The management is provided by \texttt{dOWLphin}, a Java library specifically created in order to easily load the ontologies and prepare the queries. The underlying library is \texttt{Jena}, one of the most common collections of API for the Semantic Web, that is very handy because it can directly deal with triples. As a front-end GUI, the program \texttt{QuAny} was used, which was born inside the experiment too and allows one to query against local and remote ontologies, and save on disk the corresponding results, for future verification.

2.3 Results and future objectives

The query was employed to test a significant number of ontologies of \texttt{BioPortal}, the web portal of the National Center for Biomedical Ontology. This choice was not random, but motivated mainly by two reasons: the first concerns the large amount of ontologies present on the portal, coming from repositories of biomedical resources spread all over the world; the second is relative to the connection that these ontologies have with the real world in general, and with human life and medicine in particular, which are fields offering several matters for reflection on how widely knowledge of so important themes may be schematized and represented, and, most of all, on the role reasoning may have in automatically inferring new information.

Around 30% of the ontologies resulted member of the language $\mathcal{DL}<\forall_0>$, which brings good hopes for reasoning on them, given that—we remind—w.r.t. computational complexity we are in the NP-completeness realm. Concerning the remaining 70%, efficient algorithms for conversion will have to be considered and semantic tests will have to be done, as previously happened for the $\mathcal{DL}<\text{MLSS}_{\lambda,n}>$ language (cfr. \footnote{The symbol \texttt{(R)} denotes symmetric closure of \texttt{R}.}).

In Appendix \footnote{The symbol \texttt{(R)} denotes symmetric closure of \texttt{R}.} a table shows which ontologies were recognized as members of the language $\mathcal{DL}<\forall_0>$. 

\[14\]
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A ANALYSIS OF THE SPARQL QUERY

As we are going to see in the implementation, to write declaratively what an algorithm could do through a list of well-constructed statements is not an immediate operation to undertake. The final query is the result of various logical lines of argument concerning the conversion from $DL^\forall\pi_0^-$-constructs into those of RDF(S)/OWL(2), opportunely applied to some test ontologies.

From Table 1.3, one infers that, for the ontology under examination to be considered part of the family of logics seen before, the allowed elements of RDF(S)/OWL(2) are the following:

- class or property definition (rdf:type)
- top concept (owl:Thing)
- bottom concept (owl:Nothing)
- concept negation (owl:complementOf)
- intersection and union of concepts (resp. owl:intersectionOf and owl:unionOf)
- singleton (owl:oneOf)
- self concept (owl:hasSelf)
- value restriction (owl:hasValue)
- universal role (owl:topObjectProperty)
- role inverse (owl:inverseOf)
- intersection and union of roles (not present in OWL 2)
- role restrictions (not present in OWL 2)
- identity concept (not present in OWL 2)
- symmetric closure (it can be emulated by means of union and inverse of roles)
- equivalence axiom between concepts (owl:equivalentClass)
- subsumption axiom between concepts (rdfs:subClassOf)
- existential restriction (owl:someValuesFrom) only in the left part of a subsumption
- universal restriction (owl:allValuesFrom) only in the right part of a subsumption
- minimal numerical restriction (owl:minCardinality) with cardinality not greater than 1, only in the left part of a subsumption
- declaration of concept membership (rdf:type)
- declaration of role membership
- equivalence between roles (owl:equivalentProperty)
- inclusion between roles (owl:subPropertyOf)
- role chaining (owl:PropertyChainAxiom)
- transitive property (owl:TransitiveProperty)
- reflexive property (owl:ReflexiveProperty)
- asymmetric property (owl:AsymmetricProperty)

We have to add to these all the ones that can be deduced from a combination of them, such as

- disjunction between concepts (owl:disjointWith, owl:members)

\(^{15}\)Obviously, we may ignore the constructs not present in OWL 2, since they cannot be a cause of rejection of the ontology.
A ANALYSIS OF THE SPARQL QUERY

• union of disjoint concepts (owl:disjointUnionOf)
• equivalence and non-equivalence between individuals (resp. owl:sameAs and owl:differentFrom)
• empty role (owl:bottomObjectProperty)
• role domain (rdfs:domain, some cases excluded)\textsuperscript{16}
• role range (rdfs:range)
• disjunction of properties (owl:propertyDisjointWith, owl:members)
• irreflexive property (owl:IrreflexiveProperty)
• symmetric property (owl:SymmetricProperty)
• direct and inverse functional property (resp. owl:FunctionalProperty, owl:InverseFunctionalProperty)
• declaration of role non-membership (owl:NegativePropertyAssertion)

Consequently, the constructs which cause the rejection of an ontology are:

• existential restriction not in the left part of a subsumption
• universal restriction not in the right part of a subsumption
• minimal numerical restriction with cardinality greater than 1 or not in the left part of a subsumption
• qualified numerical restrictions (owl:[$\text{max}$|$\text{min}$]QualifiedCardinality, owl:qualifiedCardinality)
• maximum and exact unqualified numerical restrictions (resp. owl:maxCardinality, owl:cardinality)
• some cases of domain declaration\textsuperscript{17}
• datatype (rdfs:Datatype, owl:DatatypeProperty)

In order to create the query, we must consider that the language $\mathcal{DL}^\forall_\exists^\neg$ is very expressive and provides constructs and axioms which range over several elements of RDF(S)/OWL(2). Thus, to abbreviate the task of enumerating them, the criterion of selecting the triples not related to the language was adopted. Consequently, the result of the query will contain at least a triple if the examined ontology is to be rejected. There are as many clauses as the elements to consider, connected by the \texttt{UNION} operator; thus, if at least a match is found, a non empty result will be obtained, i.e., the analyzed ontology will not be a member of the language.

Now, let us analyze the correctness of the query in detail (the relative row number is indicated in brackets, when necessary).

• The first clause (lines 7-19) includes the triples corresponding to existential restrictions (line 8). Yet, not all of them contribute to the rejection of the ontology, but only those which are not in the left part of a subsumption. Thus, in line 10 we force their exclusion, provided that any is found. If this is not the case, we find a match, according to line 8; otherwise, we must control that neither of the following cases occurs (lines 11-17):\textsuperscript{18}
  
  – the anonymous node corresponding to a restriction is in the right part of any triple (line 12); that allows one to include all the axioms with the restriction and the various operators (e.g., union, intersection, complement, etc.) which work on lists and single classes in the right part;
  
  – the above-mentioned node is in the left part of a triple corresponding to an axiom (lines 13-16): that allows one to include single and multiple equivalences and disjunctions.

• The second clause (lines 19-33) includes the triples corresponding to universal restrictions (line 20). When a triple of this kind is found, in order for a matching to be valid, it is also necessary to check that at least either of the following cases occurs (lines 22-31):

  – the anonymous node corresponding to a restriction is in the right part of a triple (line 23), but this triple is not a subsumption (line 24), nor that node is the domain of a property (line 25);

\textsuperscript{16}Role domain corresponds to the DLs’ axiom $\exists R. \top \sqsubseteq C$, so it is necessary to verify that $C$ is satisfactorily expressed by the language.
\textsuperscript{17}Cf. footnote\textsuperscript{16}
\textsuperscript{18}The second-level \texttt{MINUS} operator could be optimized by including the various triples contained in its clauses after line 8; nonetheless, we must not forget that the \texttt{matching} of triples is notoriously not very much efficient operation: the choice of double-nesting concurs to avoid that SPARQL engine performs useless searches when no subsumption in line 10 is found.
the above-mentioned node is in the left part of a triple (line 27), but it is not part of the definition of the
restriction itself (lines 28-30) (otherwise, an ever-false condition would be represented): that is to control
that the restriction is neither in the left part of an axiom, nor in the left part of some class construct.

• The third clause (lines 33-46) includes the triples corresponding to an operator of minimal cardinality (line
34). Here we proceed (line 36 and lines 39-43) as in the first clause, with the difference (line 37) that the
 cardinality value must be not greater than 1 too.19

• The remaining clauses (lines 47-51) check for datatype (lines 47 and 48), qualified cardinality (line 49: the
 onClass property is peculiar to this kind of restriction), exact and maximum cardinality (lines 50 and 51)
triples.

• For the purpose of accelerating the execution, the use of the LIMIT operator (line 52) reduces the size of
results to only one element, which is enough to reject the ontology.

1 PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
2 PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
3 PREFIX owl: <http://www.w3.org/2002/07/owl#>
4
5 SELECT *
6 WHERE {
7 { ?left owl:someValuesFrom ?class .
8   MINUS {
9     ?left rdfs:subClassOf ?right .
10     MINUS {
11       {?s ?p ?left . } UNION
12       {?left owl:equivalentClass ?right . } UNION
13       {?left owl:disjointWith ?right . } UNION
14       {?left owl:members ?right . } UNION
15       {?left owl:disjointUnionOf ?right . }
16     } UNION {
17     } }
18   } UNION {
19   ?restr owl:allValuesFrom ?class .
20   {
21     { ?x ?prop ?restr .
22     MINUS { ?x rdfs:subClassOf ?restr . }
23     MINUS { ?x rdfs:domain ?restr . }
24     } UNION {
25     } }
26   } UNION {
27   ?left owl:minCardinality ?num .
28   MINUS {
29     {?s ?p ?left . } UNION
30     {?left owl:equivalentClass ?right . } UNION
31     {?left owl:disjointWith ?right . } UNION
32     {?left owl:members ?right . } UNION
33     {?left owl:disjointUnionOf ?right . }
34   }
35  }
36
37  }
38
39
40
41
42
43
44

Footnote 18 holds also for the nested MINUSes.
A ANALYSIS OF THE SPARQL QUERY

\{
\}

\} UNION

\{ ?s \?p owl:DatatypeProperty . } UNION

\{ ?s \?p rdfs:Datatype . } UNION

\{ ?s owl:onClass ?o . } UNION

\{ ?s owl:cardinality ?o . } UNION

\{ ?s owl:maxCardinality ?o . }

\} LIMIT 1
B TEST AGAINST BIOPORTAL ONTOLOGIES

The SPARQL query was tested against the ontologies of BioPortal, available at the link [http://rest.bioontology.org/biopont/](http://rest.bioontology.org/biopont/). The API KEY is an identifier for the registered users. The following table associates the ID of the previous URL to the symbolic name of the correspondent ontology and highlights the ones which belong to the language.

| ID      | Name                                      | Res | ID   | Name                                      | Res |
|---------|-------------------------------------------|-----|------|-------------------------------------------|-----|
| 1033    | NMR Metabolomics Investig.                | N   | 1362 | Hymenoptera Anatomy                       | Y   |
| 1039    | Proteomics Data                           | N   | 1369 | Physical Fields                           | Y   |
| 1052    | Protops                                    | N   | 1381 | NIF Dysfunction                          | Y   |
| 1054    | Amino-acid                                | N   | 1393 | Information Artifacts                     | N   |
| 1056    | Basic Vertebrae Anatomy                   | N   | 1394 | Syndromeal Surveillance                   | N   |
| 1058    | SNP                                        | N   | 1398 | Language Disorder in Autism               | Y   |
| 1059    | Computer-based Patient Record              | N   | 1399 | Pilot ontology                           | N   |
| 1060    | Epoch Clinical Trial                      | N   | 1401 | Nursing Practice                         | N   |
| 1061    | Pharmacogenomics                          | N   | 1402 | NIF Cell                                 | N   |
| 1068    | Subcellular Anatomy                       | N   | 1406 | LinkingKing2PEP                          | N   |
| 1082    | Gene Regulation (GRO)                     | N   | 1407 | Description of Dynamics                  | N   |
| 1083    | NanoParticles                              | N   | 1409 | PKO Re                                   | Y   |
| 1084    | NIFSTD                                    | Y   | 1410 | Kinetic Simulation Algorithm              | N   |
| 1086    | Disease Genetic Investigation              | N   | 1411 | Functioning, Disability and Health        | N   |
| 1087    | Geographical Regions                      | Y   | 1413 | Software                                 | N   |
| 1088    | MuHCO                                      | N   | 1414 | General Medical Science                   | Y   |
| 1089    | BRINLex                                    | N   | 1415 | CTCAE                                    | Y   |
| 1092    | Infectious Diseases                       | N   | 1417 | Influenza                                | N   |
| 1100    | Genetic Intervals                          | N   | 1418 | TOL                                      | N   |
| 1104    | Biomedical Resource                       | N   | 1438 | Breast tissue cell lines                  | N   |
| 1106    | Gene Regulation (BOOTStrep)               | N   | 1439 | General Formal (GFO)                     | N   |
| 1116    | Bleeding History Phenotype                | N   | 1440 | General Formal (GFO-Bio)                 | N   |
| 1122    | Skin Physiology                           | N   | 1444 | Chemical Information                     | N   |
| 1123    | Biomedical Investigations                 | N   | 1461 | Translational Medicine                   | N   |
| 1126    | Family Health History                     | N   | 1484 | External Causes of Injuries              | N   |
| 1128    | Comparative Data Analysis                 | N   | 1487 | Body System                              | Y   |
| 1130    | Cancer Research and Mgmt                  | N   | 1488 | SysMO-JERM                               | Y   |
| 1131    | MGED                                       | N   | 1489 | Adverse Events                           | N   |
| 1134    | BioTop                                     | N   | 1494 | Tissue Microarray                        | N   |
| 1136    | Experimental Factors                      | Y   | 1497 | PMA 2010                                 | N   |
| 1141    | Physics for Biology                       | N   | 1500 | RNA                                      | N   |
| 1142    | Cardiac Electrophysiology                 | Y   | 1501 | Neomark Oral Cancer-based                | N   |
| 1146    | Electrocardiography                       | N   | 1505 | MicroRNA Target Prediction               | N   |
| 1149    | Dermatology Lexicon                      | N   | 1515 | Interaction Network                      | Y   |
| 1172    | Vaccines                                  | N   | 1521 | Neural Motor Recovery                    | Y   |
| 1183    | Lipids                                     | N   | 1522 | BioPAX                                   | N   |
| 1190    | Parasite Lifecycle                        | N   | 1523 | OROE-SBC                                 | N   |
| 1192    | Proteomics Pipeline Infrastructures       | N   | 1524 | OBOE                                     | N   |
| 1237    | Situation-based Access Control            | N   | 1530 | Animal natural history                   | N   |
| 1247    | GenSpecies                                | N   | 1532 | SemanticScience                         | Y   |
| 1249    | Smoking Behavior Risk                     | N   | 1533 | BioAssay                                | N   |
| 1290    | ABA Adult Mouse Brain                     | Y   | 1534 | Apollo-aksesios                         | Y   |
| 1304    | Breast Cancer Grading                     | N   | 1537 | Bruceeliosis                            | N   |
| 1314    | Cell Line (2)                             | N   | 1538 | Roles                                    | Y   |
| 1321    | Neural ElectroMagnetic Ontology           | N   | 1540 | Drug Discovery Investigations            | N   |
| 1332    | Basic Formal Ontology                     | Y   | 1541 | Cell Line (MCCL.2)                      | N   |
| 1335    | Parasite Experiments                      | Y   | 1550 | PHARE                                    | N   |