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Highlights

- Insights from psychology and the philosophy of language help understanding of how people comprehend and reason with Description Logics
- The use of natural language in knowledge representation languages can assist comprehension but also create ambiguity
- Alternative or additional Manchester OWL Syntax keywords can significantly improve comprehension
- An understanding of De Morgan’s Laws and the analogous duality laws for restrictions would aid reasoning with Manchester OWL Syntax
- Future development of knowledge representation languages should take account of psychological theories of reasoning and of how natural language is used

Improving comprehension of Knowledge Representation languages: a case study with Description Logics

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Abstract

Knowledge representation languages are frequently difficult to understand, particularly for those not trained in formal logic. This is the case for Description Logics, which have been adopted for knowledge representation on the Web and in a number of application areas. This work looks at the difficulties experienced with Description Logics; and in particular with the widely-used Manchester OWL Syntax, which employs natural language keywords. The work comprises three studies. The first two identify a number of difficulties which users experience, e.g. with negated intersection, functional properties, the use of subproperties and restrictions. Insights from cognitive psychology and the study of language are applied to understand these difficulties. Whilst these difficulties are in part inherent in reasoning about logic, and Description Logics in particular, they are made worse by the syntax. In the third study, alternative syntactic constructs are proposed which demonstrate some improvement in accuracy and efficiency of comprehension. In addition to proposing alternative syntactic constructs, the work makes some suggestions regarding training and support systems for Description Logics.

Keywords: Description Logics; Manchester OWL Syntax; User studies; Psychological theories of reasoning

1 Introduction

Knowledge representation (KR) languages are in common use to describe domains ranging from biology to finance. These languages are typically used by both computer scientists and domain experts. Early KR languages frequently employed the frame-based paradigm, developed by Minsky (1975), and inspired to a certain extent by psychological considerations[1]. In Minsky's (1975) approach *frames*, i.e. individual entities, have *terminals*, occupied by *assignments*, either by default or explicitly. This is, to an extent, analogous to the model used in object-oriented programming. An initial proposal was that frame-based representation be used for the Semantic Web (Lassila & McGuinness, 2001).

In fact, an alternative paradigm was adopted for the Semantic Web, that of Description Logics (DLs). DLs, and a reason for their adoption, are explained in Section 2. Their adoption was in the form of a family of W3C-standardized languages known as OWL, a permuted acronym of Web Ontology Language (W3C, 2001). As a result, DLs are now the dominant languages for specifying ontologies (Warren et al., 2014b). Moreover, they have been heavily studied by logicians; their computational properties are well understood and efficient reasoners have been developed. The initial interest by logicians also meant that early syntaxes were influenced by formal logic, and were perceived as not being ideal for domain experts with little training in logic and computer science[2]. In response to this, the

[1] Although psychologically inspired, the frame-based approach has been placed on a rigorous logical foundation, e.g. see Kifer et al. (1995).
[2] As will be discussed later, recent work has challenged this view (Alharbi et al., 2017).

Manchester OWL Syntax (MOS) (Horridge et al., 2006) was developed, making use of English keywords[3]. MOS is now a widely-used syntax.

Throughout these developments, there has been relatively little research into the difficulties which users of knowledge representation languages experience and the benefits, or otherwise, of the use of natural language. The research described in this paper investigates the difficulties which people experience in understanding and reasoning with DLs, in particular when expressed using MOS. The work takes ideas from the theory of reasoning in cognitive psychology and from the study of language, and applies these ideas to understand the difficulties experienced.

Section 2 provides an introduction to DLs and to the difficulties experienced with their use. Section 3 then provides an overview of various theories of reasoning developed by psychologists, and also some ideas from the study of language. Section 4 discusses the methodology used in the subsequent studies. Section 5 then describes the initial, exploratory study. This study focussed on commonly used DL constructs and identified a number of difficulties. The second study, described in section 6, investigated these difficulties in more detail, and also looked at some additional DL constructs. These studies suggested some modifications to the syntax which were investigated in a third study, described in section 7. Finally, section 8 discusses some implications of the work and makes some proposals for future research.

2 Description Logics, OWL and the Manchester OWL Syntax

This section provides a brief overview of DLs and the MOS syntax. It also describes some previous research into the difficulties which ontology developers experience with DLs.

2.1 Description Logics – overview

DLs are based on subsets of First Order Logic (FOL). However, FOL is concerned with defining and manipulating *propositions*; quantifiers are used to define propositions and Boolean operators to combine and negate them. DLs provide a language for *individuals* and *classes*; restrictions are used to define classes and Boolean concept constructors to combine and complement those classes. This will be illustrated in the next subsection. For an introduction to the theory of DLs, including the OWL standard, see Baader et al. (2017).

A key feature of DLs is the use of the Open World Assumption (OWA). The absence of a fact from a DL knowledgebase does not imply that the fact is not true. This contrasts with the Closed World Assumption (CWA) commonly assumed in database usage. Thus, if *Jane Smith* is not specified as the employee of a particular company in a DL knowledgebase, we cannot assume that she is not a company employee. We can only know that *Jane Smith* is not an employee if this information is in the knowledgebase, or can be deduced from other knowledgebase information. Another aspect of the OWA is that two names may refer to the same entity; *Jane Smith* and *J. Smith* may be the same person. We can only know they are

[3] MOS can be regarded as a Controlled Natural Language (CNL). It is, however, very restricted in its use of English, and Kuhn (2014), in a survey of CNLs, regards MOS as not sufficiently natural to be classified as a CNL. A number of DL languages have been developed which might more genuinely be regarded as CNLs. Schwitter et al. (2008) provide a comparison of three of these. Warren (2017; Section 2.5.3) provides a discussion of CNLs for DLs.

different if the knowledgebase explicitly says so, or if this can be deduced from other information. The OWA was a major reason for the adoption of DLs as a knowledge representation language for use on the World Wide Web (WWW). Unlike knowledge in corporate databases, knowledge on the WWW is rarely complete. The OWA also makes DLs appropriate for certain application areas, e.g. biological research (Stevens et al., 2007). However, the OWA does present difficulties. Rector et al. (2004) claim that it is "the biggest single hurdle to understanding OWL and Description Logics".

DLs are concerned with three types of entities:

- classes
- individuals, or instances, which are members of the classes
- object properties, which are defined between members of particular classes

As an example, we might have classes *Person* and *Dog*, with individuals *Tom* and *Rover* respectively, and a property *has_pet*, so that we could include a fact in the knowledgebase: *Tom has_pet Rover*. Here *Tom* is the subject, and *Rover* the object of the property *has_pet*. The OWL standard also includes datatype properties, between individuals and literals. We do not discuss these further as we do not believe that the problems of comprehension[4] which they pose will be substantially different from those posed by object properties.

2.2 Syntax and standardization

Since DLs were designed by logicians, the initial syntaxes were based on formalisms from logic. An example of this is the 'German DL' syntax. This used , , and ¬ for union, intersection and complement. Krötzsch et al. (2012) note that, by analogy with logic, these three operations are also referred to as disjunction, conjunction and negation. The existential ( ) and universal quantifier ( ) symbols are used to represent restrictions. For example: *P.X* defines a class containing those individuals which are the subject of a property *P* possessing an object in *X*, i.e. all the individuals *a* for which an individual *b* exists, such that *a P b* and *b* *X*. Note that, although we are using the symbol for existential quantification, we are dealing with classes, not propositions, and the symbol is being used in a different way to its use as a quantifier.

Similarly, *P.X* defines a class containing all elements *a* such that, either:

- whenever *a* is the subject of an instance of *P*, the object is in the class *X*, or
- *a* is never the subject of an instance of *X*.

The second possibility is known as the 'trivial satisfaction of the universal restriction'. It corresponds to the convention in logic that any property holds for every element of the empty set.

The adoption of DLs for use on the WWW led to the definition of the Web Ontology Language (OWL), and this was accompanied by a variety of alternative syntaxes to German DL. Some of these were perceived as being verbose, and MOS was developed to be both relatively succinct and intelligible to non-logicians (Horridge et al., 2006; Horridge & Patel-Schneider, 2008). The chief features of MOS, as used in the studies reported in this paper, are shown in Table 1. The key points to note are that:

[4] For brevity, we use the word comprehension to mean not just the interpretation of DL statements but also reasoning about those statements.

- *or*, *and* and *not* are used for union, intersection and complement. This is consistent with the use of the terms *disjunction*, *conjunction* and *negation*.
- *some* and *only* are used for the existential and universal restrictions. Examples of this usage are shown later.
- Properties can be defined to have the following characteristics: transitive; functional; inverse functional; symmetric; asymmetric; reflexive; and irreflexive. Only the first four of these are used in the work reported here.

MOS is used in the Protégé ontology editor[5], which has been widely adopted (Warren et al., 2014b).

Table 1 Subset of MOS used in the studies

	Syntax	**Semantics**
Entity declarations	*Class X*	*X* a class.
	Individual a	*a* an individual.
	Property P	*P* a property.
Class expressions	*X or Y*	union of *X* and *Y*.
	X and Y	intersection of *X* and *Y*.
	not X	complement of *X*.
Restrictions	*P some X*	the existential restriction, i.e. the class of individuals who are the subject of the property *P* with object in the class *X*.
	P only X	the universal restriction, i.e. the class of individuals which are the subject of the property *P*, with objects only in *X*, plus those individuals which are not the subject of *P*.
Class axioms	*X SubClassOf Y*	*X* a subclass of *Y*, i.e. if an individual is in *X*, it is also in *Y*.
	X EquivalentTo Y	*X* and *Y* are equivalent classes, i.e. if an individual is in *X*, it is also in *Y*, and vice-versa.
	X DisjointWith Y	*X* and *Y* are disjoint, i.e. if an individual is in *X* it is not in *Y*, and vice-versa.
	Z DisjointUnionOf W, X, Y é	*Z* comprises all the individuals in *W*, *X*, and *Y* …, and no other individuals. Moreover, *W*, *X*, and *Y* are pairwise-disjoint, i.e. there are no individuals contained in more than one of these classes.
	P Domain X	All subjects of the object property *P* are in class *X*. Equivalent to *P some Thing SubClassOf X*.
	P Range X	All objects of the object property *P* are in class *X*. Equivalent to *Thing SubClassOf P only X*.
Individual axioms	*a Type X*	*a* a member of class *X*.
	a DifferentFrom b	*a* and *b* different individuals.
Property axioms	*P SubPropertyOf Q*	*P* is a subproperty of *Q*, i.e. if *a P b*, then *a Q b*.
	P InverseOf Q	*P* and *Q* are mutually inverse properties.
	P Characteristics transitive é	P has property characteristics, e.g. transitive.

[5] http://protege.stanford.edu/

2.3 Difficulties using DLs

Ontology developers, particularly non-logicians, experience difficulties using DLs. Rector et al. (2004), based on their experience of teaching OWL DL, identified several such difficulties. They were using 'Manchester House Style', a precursor to MOS which used *and* and *or* for conjunction and disjunction, and *someValuesFrom* and *allValuesFrom* for the existential and universal restrictions. The difficulties they identified included: a tendency to assume that *allValuesFrom* implies *someValuesFrom*, i.e. a tendency to overlook the second of the two possibilities associated with the universal restriction; confusion between *and* and *or*; and confusion between *P someValuesFrom (not X)* and *not (P someValuesFrom X).*

Some difficulties arise from the keywords used. Other difficulties are inherent in DL but can be exacerbated or mitigated by choice of keywords. In the former category, the confusion between *and* and *or* is caused by the particular choice of these keywords; as will be argued later, *intersection* and *union* are less ambiguous. In the latter category, the tendency to overlook the 'trivial satisfaction of the universal restriction', as discussed in subsection 2.2, is inherent in DL but, as also will be discussed later, can be made worse or mitigated by the choice of syntax.

Rector et al. (2004) also recommended writing paraphrases of OWL statements. In these paraphrases, in anticipation of the later MOS, the universal restriction was represented using *only*. The existential restriction was represented using a combination of keywords. For example, a paraphrase of 'Pizza restriction (hasTopping someValuesFrom Tomato)' would be '*any* pizza which, *amongst other things*, has *some* tomato topping'. The inclusion of the phrase *amongst other things* recognises a user difficulty which will be further discussed in Sections 6 and 7.

Difficulties of comprehension can arise when debugging ontologies. After executing a reasoner, ontology developers may be confronted with an unexpected inference, or *entailment*. Whilst such an inference will be a logical consequence of the ontology axioms, the developer may regard it as incorrect from the domain perspective. Typically, ontology development systems can then be requested to provide a *justification*, defined as "a minimal subset of an ontology that is sufficient for an entailment to hold" (Horridge et al., 2011). However, understanding why the justification leads to the entailment can be difficult. Horridge et al. (2011) developed an intuitive model for the cognitive complexity of a justification and compared this with the difficulty actually experienced. They did this by presenting study participants with some justifications and corresponding putative entailments, and asking participants to indicate whether the entailment was, or was not, valid. They used the German DL syntax, with abstract names, e.g. *C1*, *C2* for classes and *prop1*, *prop2* for properties, which avoided participants making use of pre-existing domain knowledge. Their model "fared reasonably well" in predicting which questions study participants would find difficult and which they would find easy.

Nguyen et al. (2012) were interested in providing proof trees, in English, to explain why an entailment follows from a justification. They identified 51 deduction steps which could be used to create the proof trees and tested out the comprehensibility of these deduction steps on study participants. To do this, they presented a set of axioms and a putative inference and asked participants to confirm or refute the conclusion. However, to prevent the influence of pre-existing domain knowledge, they used a combination of meaningless words ('kalamanthis', 'tendriculos'), meaningful words ('plant', 'animal') and also words which are not real English but have a semblance of being real words (‘merfolk’, ‘lizardfolk’). Performance on these deduction rules varied widely. The easiest achieved 100% correct responses; the most difficult 4%. The latter required an understanding of the trivial satisfaction of the universal restriction.

3 Human reasoning and human language

This section describes the insights from reasoning studies and language studies which are used to guide and explain the work to be described later.

3.1 Theories of reasoning

Early theories of reasoning assumed “an unconscious logical calculus” which later was assumed to contain “formal rules of inference” (Johnson-Laird, 2010; page 194). The expectation was that people reason using formal rules of logic, similar to those used by a trained logician. These theories are variously referred to as *sentential*, *rule-based* (Stenning & Yule, 1997) or *mental logic* (Oaksford & Chater, 2001). The phrase *rule-based* will be used here, to emphasize the difference from the *model-based* theory described later.

An example of a rule-based theory is that developed by Rips (1983) for propositional reasoning. The theory employs a set of logical rules. Associated with each rule is an ‘availability parameter’, representing the probability of being able to retrieve and use the rule. From these parameters, the probability of being able to construct a particular chain of reasoning can be calculated. In his study, Rips presented participants with questions consisting of axioms and a putative inference. Participants were required to indicate whether the inference was “necessarily true” or “not necessarily true”. Based on the results of this experiment, Rips estimated the availability parameter for each of his rules.

Braine (1978) provides another example of the rule-based theory applied to propositional logic. His theory accepts that the rules of human reasoning may not always correspond to those used in standard logic. For example, he argues that *if p then q* has a directionality, from *p* to *q*, in natural language which is absent from standard logic. In everyday discourse we are not concerned with what happens when *p* is not true and would not normally associate a truth value with the statement when *p* is false. Braine’s (1978) natural propositional logic is based on the rules he claims we ordinarily use.

However, people do not always reason entirely by the application of formal rules. A classic early example of this is Wason’s selection task (Wason, 1968), where participants are required to interpret rules in order to correctly select cards. The model-based theory was developed to explain this and other experimental results. The essence of this theory is that people construct mental models of reality and then require any inferences to be consistent with those models. Ehrlich and Johnson-Laird (1982) describe an early attempt to use mental models to explain experimental results relating to the layout of objects in two-dimensional space. However, mental models can be used to represent more abstract situations. Bucciarelli and Johnson-Laird (1999), for example, interpret relative difficulties with syllogisms in terms of mental model theory. Johnson-Laird (2005) provides an overview of mental model theory, whilst Johnson-Laird (2004) puts the theory in its historical context, tracing it back to the work of the American logician C.S. Peirce, through Wittgenstein’s

(1922) picture theory of meaning, and Craik's (1967) view that cognition is based on forming models of the world.

As an example, consider conjunction, e.g. *there is a circle and there is a triangle*. Using C and T to represent circle and triangle, this is represented by one mental model:

C T

Exclusive disjunction, *there is a circle or there is a triangle, but not both*, requires two mental models:

C

T

Inclusive disjunction, *there is a circle or there is a triangle, or both*, requires three mental models:

C T

C

T

When dealing with a statement in propositional logic, the set of mental models corresponds to an expression in disjunctive normal form, with each mental model corresponding to a disjunct (Johnson-Laird et al., 1992). The essence of the mental model theory is that, when there is a requirement for more than one mental model, human reasoners are apt to overlook one or more of the models. This leads to the kinds of errors which humans frequently display.

The distinction between the rule-based and mental model theories is analogous to that between syntactic and semantic approaches in logic. Indeed, Braine and O'Brien (1998) use the phrase "syntax of thought" when writing about their rule-based theory. In contrast, Johnson-Laird and Byrne (1991, Prologue) use the phrase "an internal representation".

In addition to the rule-based and model-based theories, Halford et al. (1998) have developed a theory of reasoning based on ascribing a *relational comple*xity (RC) to each reasoning step. They give the following example: *John is taller than Mary* and *Mary is taller than Sue*, leading to the inference *John is taller than Sue*. This involves maintaining three items in working memory at the same time, and hence the RC is three. Halford et al. (2005) found that there was no significant difference in accuracy or time between problems with RC two or three. However, problems of RC four were answered significantly less accurately and in significantly longer time than problems of RC three. Problems of RC five were not answered significantly better than chance. RC theory can be regarded as complementary to both the other theories.

3.2 The ambiguity of natural language

MOS makes use of *and* and *or* to represent intersection and union. This presumably arose because, if we take *P(x)* and *Q(x)* to be predicates representing membership of classes C_P and C_Q, then *(P and Q)(x)* represents membership of the intersection of those classes, whilst *(P or Q)(x)* represents membership of the union. However, as already noted, DL, unlike FOL, is concerned with classes. The following examples illustrate the ambiguity which arises when *and* and *or* are used to represent class operations. The examples are taken from Partee and Rooth (1983); the analysis is the authors'. First consider three sentences constructed using *and*:

1. Susan will retire and buy a farm.
2. John and Mary are in Chicago.
3. She was wearing a new and expensive dress.

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