Modelling the Semantics of Adjectives in the Ontology-Lexicon Interface

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Abstract

The treatment of the semantics of adjectives is notoriously challenging, and we consider this problem in the context of the so called ontology-lexicon interface which attempts to capture the semantics of words by reference to an ontology in description logics or some other, typically first-order, logical formalism. The use of first order logic (hence also description logics), while effective for nouns and verbs, breaks down in the case of adjectives. We argue that this is primarily due to a lack of logical expressivity in the underlying ontology languages. In particular, beyond the straightforward *intersective adjectives*, there exist *gradable adjectives*, requiring fuzzy or non-monotonic semantics, as well as *operator adjectives*, requiring second-order logic for modelling. We consider how we can extend the ontology-lexicon interface as realized by extant models such as *lemon* in the face of the issues mentioned above, in particular those arising in the context of modelling the ontological semantics of adjectives. We show how more complex logical formalisms that are required to capture the ontological semantics of adjectives can be backward engineered into OWL-based modelling by means of pseudo-classes. We discuss the implications of this modelling in the context of application to ontology-based question answering.

1 Introduction

Ontology-lexicon models, such as *lemon* (Lexicon Model for Ontologies) (McCrae et al., 2012), have become an important model for handling a number of tasks in natural language processing. In particular, such ontology-lexica are built around the separation of a lexical layer describing how a word or phrase acts syntactically and morphologically, and a semantic layer describing how the meaning of a word is expressed in a formal logical model, such as OWL (Web Ontology Language) (Deborah L. McGuinness and others, 2004). It has been shown that this principle known as *semantics by reference* (Buitelaar, 2010) is an effective model that can support the task of developing question answering systems (Unger and Cimiano, 2011) and natural language generation (Cimiano et al., 2013) over backends based on Semantic Web data models. The Pythia system, which builds on the *lemon* formalism to declaratively capture the lexicon-ontology interface, for example, has been instantiated to the case of answering questions from DBpedia (Unger and Cimiano, 2011) However, as has been shown by the Question Answering over Linked Data (Lopez et al., 2013, QALD) benchmarking campaigns, there are many questions that can be asked over this database that require a deeper representation of the semantics of words, adjectives in particular. For example, questions such as (1a) require understanding of the semantics of 'high' in a manner that goes beyond the expressivity of OWL. The answer given in the QALD dataset for this question is shown in (1b). In particular, the interpretation of this question involves the understanding of how the word 'high' relates to the property `dbo:elevation`, including ordering and subset selection operations, the expression of the semantics of the phrase in a formal manner.

1. (a) What is the highest mountain in Australia?

(b)
```
SELECT DISTINCT ?uri WHERE {
  ?uri rdf:type dbo:Mountain .
  ?uri dbo:locatedInArea res:Australia .
  ?uri dbo:elevation ?elevation .
} ORDER BY DESC(?elevation) LIMIT 1
```

It has been claimed that first-order logic and thus by extension description logics, such as OWL, "fail decidedly when it comes to adjectives" (Bankston, 2003). In fact, we largely agree that the semantics of many adjectives are difficult or impossible to describe in first-order logic. However, from the point of view of the ontology-lexicon interface, the logical expressivity of the ontology is not a limiting factor. In fact, due to the separation of the lexical and ontology layers in a model such as *lemon*, it is possible to express the meaning of words without worrying about the formalism used in the ontology. To this extent, we will first demonstrate that adjectives are in general a case where the use of description logics (DL) breaks down, and for which more sophisticated logical formalisms must be applied. We then consider to what extent this can be handled in the context of the ontology-lexicon, and introduce pseudo-classes, that is OWL classes with annotations, which we use to express the semantics of adjectives in a manner that would allow reasoning with fuzzy, high-order models. To this extent, we base our models on the previously introduced design patterns (McCrae and Unger, 2014) for modelling ontology-lexica. Finally, we show how these semantics can be helpful in practical applications of question answering over the DBpedia knowledge base.

2 Classification of adjectives

There are a number of classifications of adjectives. First we will start with the most fundamental distinction between *attributive* and *predicative* usage, that is the use of adjectives in noun phrases ("X is a $A\ N$") versus as objects of the copula ("X is A"). It should be noted that there are many adjectives for which only predicative or attributive usage is allowed, as shown in (3a) and (3).

2. (a) Clinton is a former president.
   (b) *Clinton is former.
3. (a) The baby is awake.
   (b) *The awake baby.

One of the principle classifications of the semantics of adjectives (for example (Partee, 2003; Bouillon and Viegas, 1999; Morzycki, 2013b)) is based on the meaning of adjective noun compounds relative to the meaning of the words by themselves. This classification is as follows (where $\Rightarrow$ denotes entailment).

Intersective (X is a $A\ N \Rightarrow X$ is $A \wedge X$ is a N) Such adjectives work as if they were another noun and indicate that the compound noun phrase is a member of both the class of the noun and the class of the adjective. For example, in the phrase "Belgian violinist" it refers to a person in the class intersection $Belgian \sqcap Violinist(X)$, and hence we can infer that a "Belgian violinist" is a subclass of a "Belgian". Furthermore, we could conclude that if the same person were a surgeon, he/she would also be a "Belgian Surgeon".

Subsective (X is a $A\ N \Rightarrow X$ is a N, but X is a $A\ N \not\Rightarrow X$ is A) Such adjectives acquire their specific meaning in combination with the noun the modify. For example, a "skilful violinist" is certainly in the class $Violinist(X)$ but the described person is 'skilful as a violinist', but not skilful in general, e.g. as a surgeon.

Privative (X is a $A\ N \not\Rightarrow X$ is a N) These adjectives modify the meaning of a noun phrase to create a noun phrase that is potentially incompatible with the original meaning. For example, a "fake gun" is not a member of the class of guns.

Another important distinction is whether adjectives are *gradable*, i.e. whether a comparative or superlative statement with these adjectives makes sense. For example, adjectives such as 'big' or 'tall' can express relationships such as 'X is bigger than Y'. However it is not possible to say that one individual is 'more former'. Most gradable adjectives are subsective (e. g.'a big mouse' is not 'a big animal' (Morzycki, 2013a)).

Finally, we consider *operator* or *property-modifying* adjectives. They can be considered the same as privative adjectives, but in this case they are understood as operators that change some property in the qualia structure of the class. For instance, we may express the adjective 'former' in lambda calculus as a function that takes a class C as input and returns the class of entities that were a member of C to some prior time point t (Partee, 2003):

$$\lambda C[\lambda x \exists t C(x,t) \cap t < \mathrm{now}]$$

Such adjectives have not only a difference in semantic meaning but can also frequently have syntactic impact, for example in adjective ordering restrictions, as they may be reordered with only semantic impact (Teodorescu, 2006), e.g.,

4. (a) A big red car.
   (b) $^?$A red big car.
5. (a) A famous former actor.
   (b) A former famous actor.

Finally, we define *object-relational* adjectives which have a meaning that expresses a relationship between two individuals or events[1], for example:

6. He is related to her.
7. She is similar to her brother.
8. This is useful for something.

3 Representation of adjectives in the ontology-lexicon interface

In general it is assumed that adjectives form frames with exactly one argument except for extra arguments given by adjuncts, typically prepositional phrases. Most adjectives are thus associated with a predicative frame, which much like the standard noun predicate frame (X is a N) is stereotyped in English as:

$$X \text{ is } A$$

For attributive usage, we associate this with a frame, which is stereotyped as it follows, where the $N?$ argument is not semantically bound, but instead obtained by syntactic unification to a noun predicate frame.

$$X \text{ is } A\ N?$$

As such, when we encounter the attributive usage of an adjective such as in 9, we understand this as the realization of two frames, given in 10.

9. Juan is a Spanish researcher.
10. (a) Juan is a researcher.
    (b) Juan is a Spanish $N?$

Note we do not provide modelling for adjectives where the meaning is unique for a particular noun phrase, such as 'polar bear', which we would capture as a normal noun phrase with meaning *ursus maritimus*.

3.1 Intersective adjectives

Intersective adjectives are the most straightforward class, as in many cases they can be modelled essentially as a noun or verb (e.g. deverbal adjectives such as 'broken'). Intersective adjectives take one argument and can thus be modelled as unary predicates in first-order logic or classes in OWL, as described by McCrae and Unger (2014). For practical modelling examples, we will use the *lemon* model, since it is the most prominent implementation of the ontology-lexicon interface.

The primary mechanism of modelling the syntax-semantics interface in the context of *lemon* is by means of assigning a *frame* as a *syntactic behaviour* of an entry and giving it *syntactic arguments*, which

[1] Our definition of relational here is borrowed from the idea of relational nouns (De Bruin and Scha, 1988) as a word that requires an argument. Our definition is also different from the one for 'relational adjectives' as proposed by (Morzycki, 2013a).

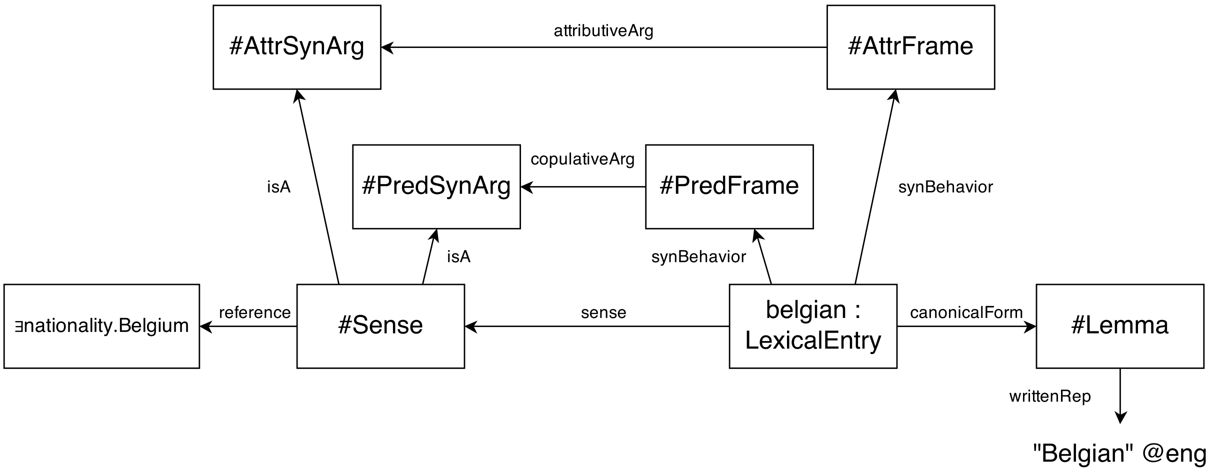

Figure 1: Modelling of an intersective adjective 'Belgian' in *lemon*

can then be linked to the *lexical sense*, which stands in proxy for a true semantic frame in the ontology. For example, the modelling of an adjective such as 'Belgian' can be achieved as follows (depicted in Figure 1)[2].

```
lexicon:belgian a lemon:LexicalEntry ;
  lemon:canonicalForm belgian:Lemma ;
  lemon:synBehavior   belgian:AttrFrame ,
                      belgian:PredFrame ;
  lemon:sense         belgian:Sense .

belgian:Lemma lemon:writtenRep "Belgian"@eng .

belgian:AttrFrame lexinfo:attributiveArg belgian:AttrSynArg .
belgian:PredFrame lexinfo:copulativeArg  belgian:PredSynArg .

belgian:sense lemon:reference [ a owl:Restriction ;
                                owl:onProperty dbpedia:nationality ;
                                owl:hasValue dbpedia:Belgium ] ;
             lemon:isA belgian:AttrSynArg , belgian:PredSynArg .
```

Note that here we use the external vocabulary LexInfo (Cimiano et al., 2011) to define the meaning of the arguments of the frame as the *attributive argument*, corresponding to the frame stereotype 'X is A N?' and the *copulative argument* for the frame stereotype 'X is A'. Furthermore, the class of Belgians is not named in our reference ontology DBpedia, so we introduce an anonymous class with the axiomatization, $\exists\, \textit{nationality}\,.\, \textit{Belgium}$. It is in fact common that the referent of an adjective is not named in an ontology and as such we tend to model denominal adjectives as classes of the form $\exists\, \textit{prop.Value}$, where *Value* is the reference of the noun from which the adjective is derived. This modelling is so common that it has already been encoded as two design patterns, called `IntersectiveObjectPropertyAdjective` and `IntersectiveDatatypePropertyAdjective` (see (McCrae and Unger, 2014)). Similarly, most deverbal adjectives refer to an event, and as such a common modelling is of the form $\exists\, \textit{theme}^{-1}.\, \textit{EventClass}$. For example, 'vandalized' may be $\exists\, \textit{theme}^{-1}.\textit{VandalismEvent}$.

3.2 Gradable adjectives and relevant observables

Gradable adjectives have a number of properties, which differentiate them from intersective adjectives:

- They occur in comparative constructions, in English with either '-er' or 'more' (Kennedy and McNally, 1999), e.g. 'smaller' and 'more frequent', as opposed to intersectives such as '*less geologi-

[2] We assume that the namespaces are defined for the lexicon as `lexicon`, e.g., `http://www.example.org/lexicon` and for the entry, e.g., `belgian` is `http://www.example.org/lexicon/belgian#`. Other namespaces are assumed to be as usual.

cal' and '*more wooden'.
- Gradable adjectives can be defined as 'scalar', since their value can ideally be measured on a scale of set degrees, which is dependent on the object of the adjective ('big' can be defined based on the number of stores of a 'building' or the height of a 'person').
- They have a context-dependent truth-conditional variability, meaning that their positive form is understood in relations to the class of the object modified by the adjective. For example, an 'expensive watch' has a different price scale to an 'expensive bottle of water'.
- They are frequently *fuzzy* (or *vague*) (Kennedy, 2007).
- There may be a minimum or maximum of the adjective's scale, which can be determined by, for example, whether they can modified by adverbs such as 'completely' or 'utterly'.

As such, we define gradable adjectives relative to a particular property. These adjectives are also called 'observable' (Bennett, 2006)[3], that is it is natural to say that 'big' refers to 'size', however it is then clear that 'small' also refers to 'size' and as antonyms they cannot both have exactly the same concept in the ontology, therefore we cannot refer directly to the property 'size' alone. As such, we introduce the concept of *covariance* and *contravariance*, which refers to whether the comparative form indicates a higher property value for the subject or the object. That is that 'big' is covariant with size, as bigger things have a higher size value, and 'small' is contravariant with size.[4] We also introduce a third concept of *absolute gradability*, which states that these objects are better described by these adjectives as they approach some ideal value. A common example of this is colours, where we may say that some object is redder than another if it is closer to some ideal value of red (e.g., RGB `0xff0000`).

While these concepts well handle the comparative usage of adjectives, the predicative and superlative usage of adjectives is complicated by three factors that we will outline below. We notice that gradable classes are not crisply defined like in the case of many intersective adjectives. In fact, while we can clearly define all people in the world as 'Belgian' or 'not Belgian', according to whom holds a Belgian passport or not, it is not easy to split the world's population into 'tall' and 'not tall' (This is known as *sorites* paradox (Bennett, 2006)). Furthermore, while it may be easy to say that someone with height 6'6" (198cm) is 'tall', it is not clear whether someone with height 6' (182cm) is 'tall', although compared to an average (different) height for a man, they are 'taller'. As such, one frequently used way to deal with this class of vague adjectives (and nouns) is via fuzzy logic (Goguen, 1969; Zadeh, 1975; Zadeh, 1965; Dubois and Prade, 1988; Bennett, 2006). Secondly, we notice that these class boundaries are non-monotonic, that is that with knowledge of more instances of the relative class we must revise our class boundaries. This is especially the case for superlatives, as the discovery of a new tallest person in the world would remove the existing tallest person in the world from the class of tallest person in the world. This non-monotonicity also affects the class boundaries of the gradable class itself. For example, in the 18th century, the average height of a male was 5'5" (165cm)[5]; as such a male of 6' would have clearly been considered tall.

It follows that each instance added to our ontology must revise the class boundaries of a gradable class, hence leading to the fact that gradable adjectives are fundamentally non-monotonic. We must also notice that gradability can only be understood relative to the class that we wish to grade, that is that while it is unclear as to whether 6' is tall for a male, given the current average height of a female being about 5'4" (162cm), it is clear that 6' is tall for a female.

We can therefore conclude that gradable adjectives are *fuzzy*, *non-monotonic* and *context-sensitive*, all of which are incompatible with the description logic used in OWL.

[3]Note that in many cases the property is quite abstract such as in 'breakable'.

[4]The use of these terms is borrowed from type systems, and resembles the concept of 'converse observables' as mentioned by ((Bennett, 2006):42). As stated by the author, adjectives often come in pairs of polar opposites (e. g. $conv(tall) = short$, and both refer to the same observable (in this case *size*). Some observables analogously hold converse relationships with other observables (e. g. $conv(flexibility) = rigidity$ or $conv(tallness) = shortness$).

[5]`https://en.wikipedia.org/wiki/Human_height`

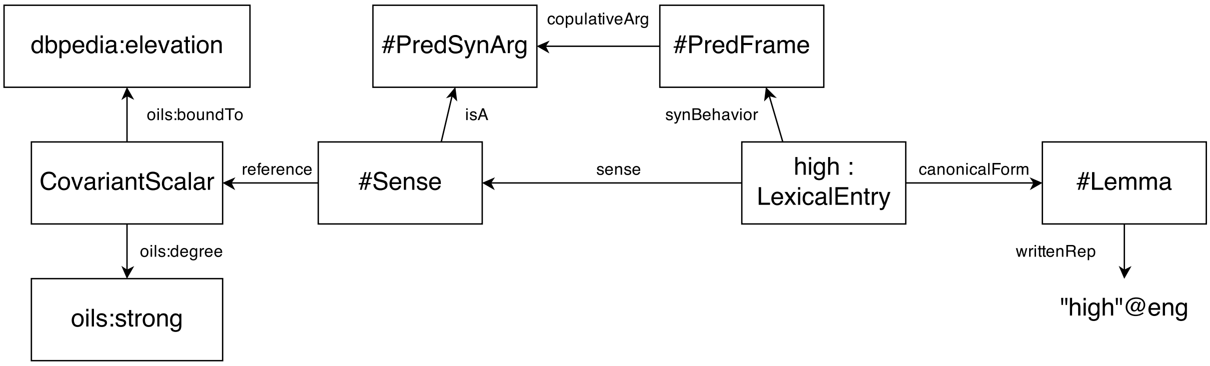

Figure 2: An example of the modelling of 'high' in *lemon*

3.2.1 Pseudo-classes in lemonOILS

Currently there are only limited models for representing fuzzy logic in the context of the Web (Zhao and Boley, 2008). In order to capture the properties of gradable adjectives, we introduce a new model, which we name *lemonOILS* (The *lemon* Ontology for the Interpretation of Lexical Semantics)[6]. This ontology introduces three new classes:

- `CovariantScalar`, indicating that the adjective is covariant with its bound property
- `ContravariantScalar`, indicating that the adjective is contravariant with its bound property
- `AbsoluteScalar`, indicating that the property represents similarity to an absolute value

In addition, the following properties are introduced to enable the description of gradable adjectives. Note that all these properties are typed as *annotation properties* in the OWL ontology, so that they do not interfere with the standard OWL reasoning.

- `boundTo` indicates the property that a scalar refers to (e.g., 'size' for 'big')
- `threshold` specifies a sensible minimal value for which the adjective can be said to hold
- `absoluteValue` is the ideal value of an absolute scalar
- `degree` is specified as `weak`, `medium`, `strong` or `very strong`, corresponding to approximately 50%, 25%, 5% or 1% of all known individuals
- `comparator` indicates an object property that is equivalent to the comparison of the adjective (e.g., an object property `biggerThan` may be considered a comparator for the adjective class `big`)
- `measure` indicates a unit that can be used as a measure for this adjective, e.g., 'John is 175 *centimetres* tall'.

Using such classes we can capture the semantics of gradable adjectives syntactically but not formally within an OWL model. As such, we call these introduced classes *pseudo-classes*. An example of modelling an adjective such as 'high' is given below (and depicted in Figure 2).

```
lexicon:high a lemon:LexicalEntry ;
  lemon:canonicalForm high:Lemma ;
  lemon:synBehavior high:PredFrame ;
  lemon:sense high:Sense .

high:Lemma lemon:writtenRep "high"@eng .

high:PredFrame lexinfo:copulativeArg high:PredArg .

high:Sense lemon:reference [
    rdfs:subClassOf oils:CovariantScalar ;
    oils:boundTo dbpedia:elevation ;
    oils:degree oils:strong ] ;
  lemon:isA high:PredArg .
```

[6]`http://lemon-model.net/oils`

As an example of a logic in which these annotations could be interpreted, we consider Markov Logic (Richardson and Domingos, 2006), which is an extension of first-order logic, in which each clause is given a cost. The process of reasoning is thus transformed into an optimization problem of finding the extension, which minimizes the summed weight of all violated clauses. As such, we can formulate a gradable adjective based on the number of known instances. For example, we can specify 'big' with respect to *size* for some class C as in (11).

11. $\forall x \in C, y \in C : size(x) > size(y) \rightarrow big_C(x) : \alpha$
    $\forall x \in C, y \in C : size(x) < size(y) \rightarrow \neg big_C(x) : \beta$

In this way, the classification of an object into 'big' or 'small' can be defined as follows. For an individual $x \in C$, the property $big_C(x)$ holds if and only if:

$$|\{y \in C, size(y) > size(x)\}|\alpha < |\{y \in C, size(y) < size(x)\}|\beta$$

where the values of α and β are related to the degree defined in the ontology.

We see that 'big' defined in this way has the three properties outlined above: it is non-monotonic (in that more individuals may change whether we consider an individual to be 'big' or not), it is fuzzy (given by the strength of the probability of the proposition $big_C(x)$), and it is context-sensitive (as whether an individual counts as big or not depends on the class C). Furthermore, our definition does not rely on defining 'big' for a given class, but instead is inferred from some known number of instances of this class. This eliminates the need to define a threshold for each individual class, or even to define the predicate big_C on a per-class basis.

3.2.2 The supervaluation theory and SUMO

Another way to capture the meaning of these vague terms can be achieved by *supervaluation semantics*. Through supervaluation theory, the modelling or positioning of *sorites* vague concepts is grounded in a judgement or meaning that lies on arbitrary thresholds, but these thresholds are based on a number of *relevant objective measures* (Bennett, 2006).

A recent extension of the SUMO ontology (Niles and Pease, 2001, Suggested Upper Merged Ontology)[7] includes default measurements (currently amounting to 300+) added to the `Artifacts`, `Devices` and `Objects` enlisted in the ontology (and marked with capitals). The compilation of `defaultMeasurements` in SUMO has been just conducted on observables, not on predicates. Given for instance an `Artifact` such as `Book`, the compilation of its default measurements would look like:

```
;;Book
(defaultMinimumHeight Book (MeasureFn 10 Inch))
(defaultMaximumHeight Book (MeasureFn 11 Inch))
(defaultMinimumLength Book (MeasureFn 5.5 Inch))
(defaultMaximumLength Book (MeasureFn 7 Inch))
(defaultMinimumWidth Book (MeasureFn 1.2 Inch))
(defaultMaximumWidth Book (MeasureFn 5.5 Inch))
```

The example for `Book` shows that the default measurements for the observable reflect a *standard* kind of book, i.e., one of the most commonly known kinds of the same artifact. As for this case, SUMO implies `Book` to be a physical object with a certain length, height and width (and possibly weight). A weakness here is that the there is no systematic connection between the `defaultMinimumHeight` and `Height` or `Width`, since these physical properties have been defined in SUMO just in terms of first-order logic, and have not been assigned default measurements yet. With *lemonOILS* we can add this information as follows:

```
sumo:Book oils:default [
    oils:defaultFor sumo:height ;
    oils:defaultMin "10in" ;
    oils:defaultMax "11in" ] .
```

Then, if we understand a lexical entry 'high' as referring to a scalar covariant pseudo-class for `sumo:height`, it is possible to understand that a 'high' object exceeds the default minimum set established for the same object and owns at the same time a value for 'high' which does not go beyond the established default maximum. A further weakness of this approach is captured by the following example:

[7] `www.ontologyportal.org`

12. Avery Johnson is a short basketball player.

Here, we see the difficulty in interpreting the sentence, as Avery Johnson is in fact of average height (5'10") but for the class of basketball players he is unusually short. While SUMO has some very specific listings of subsets for the same `Artifact`[8], SUMO does not provide a well-structured subset net for e. g. `Person`. A way to solve this bottleneck could be to introduce, for every possible subclass of `Person`, default values; as well as to introduce default values for the same Artifact in conjunction with a predicate or adjective (e. g. `BigPerson`, `BulkyPerson`). Nevertheless, this can potentially lead to an explosion in the amount of information we need to encode in the ontology. On the other side though, the SUMO default measurements serve the purpose they were originally conceived for, namely to be an arbitrary, yet computable approximation of physical measures.

3.3 Operator adjectives

Operator adjectives are those that combine with a noun to modify the meaning of the noun itself. There are two primary issues with the understanding of the adjective in this manner. Firstly, the reference of the lexical item does not generally refer to an existing item in the ontology, but rather is novel and productive, in the sense that it generates a new class. Secondly, the compositional nature of adjective-noun compounds is no longer simple, as in the cases of intersective and gradable adjectives. This means that, in order to understand a concept such as a 'fake gun', we must first derive a class of `FakeGuns` from the class of `Guns`. Thus the modified noun phrase must be an argument of the operator adjective.

To this extent we claim that it is not generally possibly to represent the meaning of an operator adjective within the context of an OWL ontology. Instead, following Bankston (Bankston, 2003), we claim that the reference of an operator adjective must be a higher order predicate. If we assume that there are operators of the form of a function, then the argument of a operator is the attributed noun phrase. As such, we introduce a frame *operator attributive*, that has one argument which is the noun. Thus we understand that the interpretation of 'fake gun' is by means of an operator $fake$, which is a function that takes a class and produces a new class, i.e., $[fake(Gun)](X)$. It is of course not possible in first-order logic to have such a function, but is in higher-order logic. As there is at the moment no agreed representation for such an operator in an ontology, it underlines the fact that more sophisticated ontology representations than first-order logic are required to understood natural language in general.

3.4 Object-relational adjectives

Object-relational adjectives are those that require a second argument, such as 'known', which can only be understood as being 'known' to some person, in comparison to 'famous'. As such, the modelling of relational adjectives is similar to we can model 'known' with the frame 'X is known to Y' and reference `foaf:knows` as:

```
lexicon:known a lemon:LexicalEntry ;
  lemon:canonicalForm known:Lemma ;
  lemon:sense known:Sense ;
  lemon:synBehavior known:Frame .

known:Lemma lemon:writtenRep "known"@eng .

known:Frame lexinfo:attributeArg known:Subject ;
  lexinfo:prepositionalObject known:Object .

known:Sense lemon:reference foaf:knows ;
  lemon:subjOfProp known:Subject ;
  lemon:objOfProp known:Object .

known:Object lemon:marker lexicon:to .
```

[8]For example, some of the subsets `Car` are: `CrewDormCar`, `GalleryCar`, `MotorRailcar`, `FreightCar`, `BoxCar`, `RefrigeratorCar`, `FiveWellStackCar`, and more.

4 Adjectives in question answering

Of the 150 training and test questions of the QALD-4 benchmark[9] for question answering over linked data, 67 contain adjectives.

Some of the occurring adjectives do not have a semantic contribution, or at least none that is separable from the noun, as exemplified in the noun phrases in (13) and (14).[10]

13. (a) $[\![$official website$]\!]$ = `dbo:website`
    (b) $[\![$national anthem$]\!]$ = `dbo:anthem`
14. (a) $[\![$official languages$]\!]$ = `dbo:officialLanguages`
    (b) $[\![$military conflicts$]\!]$ = `dbo:battle`

Otherwise, the most common kinds of adjectives among them are intersective and gradable adjectives.

All intersective adjectives denote restriction classes that are not explicitely named in DBpedia, in correspondence with the modelling proposed in Section 3.1 above, for example:

15. (a) $[\![$Danish$]\!]$ = $\exists$ `dbo:country.res:Denmark`
    (b) $[\![$female$]\!]$ = $\exists$ `dbo:gender.res:Female`
    (c) $[\![$Methodist$]\!]$ = $\exists$ `dbo:religion.res:Methodism`

In some cases these intersectives have a context-dependent and highly ontology-specific meaning, often tightly interwoven with the meaning of the noun, as in the following examples:

16. (a) $[\![$first president of the United States$]\!]$ = $\exists$ `dbo:office.` '1st President of the United States'
    (b) $[\![$first season$]\!]$ = $\exists$ `dbo:seasonNumber.1`

All gradable adjectives that occur in the QALD-4 question set can be captured in terms of *lemonOILS* as `CovariantScalar` (e.g. 'high') or `ContravariantScalar` (e.g. 'young') (cf. Section 3.2 above), bound to a DBpedia datatype property (e.g. `elevation` or `birthDate`). The positive form of those adjectives only occurs in 'how' questions, denoting the property they are bound to, for example:

17. (a) $[\![$deep$]\!]$ = `dbo:depth` in 'How deep is Lake Placid?'
    (b) $[\![$tall$]\!]$ = `dbo:height` in 'How tall is Michael Jordan?'

The comparative form denotes the property they are bound to, together with an aggregation operation, usually a filter invoking a term of comparison that depends on whether the adjective is covariant or contravariant.

18. (a) $[\![$Which mountains are higher than the Nanga Parbat?$]\!]$ =

```
SELECT DISTINCT ?uri WHERE {
 res:Nanga_Parbat dbo:elevation ?x .
 ?uri rdf:type dbo:Mountain .
 ?uri dbo:elevation ?y .
 FILTER (?y > ?x)
}
```

Finally, the superlative form denotes the property they are bound to, together with an aggregation operation, usually an ordering with a cut-off of all results except the first one, as exemplified in (19). In some cases, the superlative property is already encoded in the ontology, e.g., in the case of the property `dbo:highestPlace`.

19. $[\![$What is the longest river?$]\!]$ =

```
SELECT DISTINCT ?uri WHERE {
 ?uri rdf:type dbo:River .
 ?uri dbo:length ?l .
} ORDER BY DESC(?l) OFFSET 0 LIMIT 1
```

[9] `http://www.sc.cit-ec.uni-bielefeld.de/qald/`

[10] $[\![\cdot]\!]$ stands for 'denotes' and the prefixes `dbo` and `res` abbreviate the DBpedia namespaces `http://dbpedia.org/ontology/` and `http://dbpedia.org/resource/`, respectively.

There are some instances of operator adjectives. Examples are 'former', as in 20, which does not refer to an element in the DBpedia ontology but is instead a disambiguation clue in the given query, and 'professional', which refers to the property `dbo:occupation`, see 21.

20. $[\![$the former Dutch queen Juliana$]\!] = \texttt{res:Juliana}$
21. $[\![$professional surfer$]\!] = \exists\,\texttt{dbo:occupation.res:Surfing}$

5 Related work

The categorization of adjectives in terms of formal semantics goes back to Montague (1970) and Vendler (1968), however one of the most significant attempts to assign a formal meaning was carried out in the Mikrokosmos project (Raskin and Nirenburg, 1995). This was one of the first works to treat the case of a micro-theory of adjectives, in which the results were "machine-tractable", in that they could be formally defined by a computer. However, the applications of this were limited and no formal logic was attached to the semantic representations. Nevertheless, much of the modelling resembles ours. In particular, scalar adjectives in the Microkosmos project are modeled by association with an attribute and a range, e.g., 'big' is described as being `>0.75` (i.e., 75% of all known instances) on the `size-attribute`. Still, these classifications do not clearly separate meaning and syntax and also require a separate modelling of comparatives and class-specific meanings for many adjectives.

Amoia and Garden (2006) handled the problem of adjectives in the context of textual entailment. They analyzed 15 classes that show the subtle interaction between the semantic class (e.g., 'privative') and the issues of attributive/predicative use and gradability. Abdullah and Frost (2005) tackles the privative nature of adjectives by arguing that the adjectives modify the set themselves, in a manner that is naturally second-order. Similarly, Partee (2003) proposed a limited second-order model by means of an 'head primary principle' requiring that adjectives are interpreted within their context. Bankston's analysis (2003) however shows that the fundamental nature of many adjectives is higher-order, and provides a very sophisticated formal representation framework for this syntactic class. A more thorough discussion of non-gradable, non-intersective adjectives is given by Morzycki (2013a). Bouillion (1999) consider the case of the French adjective 'vieux' ('old'), which he interprets as selecting two different elements in the event structure of an attributed noun, that is whether the state, e.g., 'being a mayor' for 'mayor', is considered old or the individual itself. In this way, the introduction of two senses for 'vieux' is avoided, however it remains unclear if such reasoning introduces more complexity than the extra senses. In his analysis of adjectives, Larson (1998) suggests that many adjectives denote properties of *events*, rather than of simple heads or nouns (which does not fall very far from the statement, made above, that relational adjectives denote properties of kinds). Pustejovsky (1992; 1991) and Lenci (2000) state that lexical and semantic decomposition can be achieved generatively, assigning to each lexical item a specific qualia structure. For instance, in an expression like:

22. The round, heavy, wooden, inlaid magnifying glass
    - 'round' represents the *Formal* role (giving indications of shape and dimensionality)
    - 'heavy' and 'wooden' is the *Constitutive* role and indicates the relation between the object and its parts (e. g. by specifying weight, material, parts and components)
    - 'inlaid' is the *Agentive* role of the lexical item, denoting the factors that have been involved in the generation of the objects, such as creator, artifact, natural kind, and causal chain
    - 'magnifying' describes the *Telic* role of 'glass', since it shows its purpose and function

Finally, Peters and Peters (2000) provide one of the few other practical reports on modelling adjectives with ontologies, in the context of the SIMPLE lexica. This work is primarily focussed on the categorization of by means of intensional and extensional properties, rather than due to their logical modelling.

6 Conclusion

In this paper we have presented a method for modelling adjectives with the ontology-lexicon model, *lemon*. In particular, we found that adjectives frequently go beyond the first-order logic model used by OWL, but instead require models that are non-monotonic, fuzzy and second-order. As such, we conclude that more sophisticated semantic models are required to represent the semantics of such words.

However, the separation of syntax and semantics remains a robust model, which can be easily adapted to the task of representing adjectives. As a final note, we consider the claims that not all languages have adjectives[11], but based on our analysis of realistic questions as applied in QALD, we nevertheless believe that this model should be applicable to a range of domains and languages with little issue, even if further validation is necessary.

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