Black-box Testing of First-Order Logic Ontologies Using WordNet

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Abstract
A long-standing dream of Artificial Intelligence (AI) has pursued to enrich computer programs with commonsense knowledge enabling machines to reason about our world. This paper offers a new practical insight towards the automation of commonsense reasoning with first-order logic (FOL) ontologies. We propose a new black-box testing methodology of FOL SUMO-based ontologies by exploiting WordNet and its mapping into SUMO. Our proposal includes a method for the (semi-)automatic creation of a very large set of tests and a procedure for its automated evaluation by using automated theorem provers (ATPs). Applying our testing proposal, we are able to successfully evaluate a) the competency of several translations of SUMO into FOL and b) the performance of various automated ATPs. In addition, we are also able to evaluate the resulting set of tests according to different quality criteria.

Keywords: Black-box testing, Automated theorem proving, Knowledge representation

1. Introduction
Recently, Artificial Intelligence (AI) has shown great advances in many different research areas, but there is one critical area where progress has shown limited progress: commonsense representation and commonsense reasoning [23, 24, 7]. The work introduced in this paper proposes to advance a step forward in this research line by providing a new black-box testing methodology of first-order logic (FOL) SUMO-based ontologies by exploiting WordNet and its mapping into SUMO.

Formal ontology development is a discipline whose goal is to derive explicit formal specifications of the terms in a domain and relations among
As other software artefacts, ontologies have to fulfill some previously specified requirements. Usually both the creation of ontologies and the verification of its requirements are manual tasks that require a significant amount of human effort. In the literature, there exist some methodologies that collect the experience in ontology development \cite{14} and, more concretely, in ontology verification \cite{12}.

Roughly speaking, the methodologies for validating functional requirements of ontologies are based on the use of competency questions (Cs) \cite{17}. That is, according to the requirements of a given ontology, a set of goals that the ontology is expected to answer is defined for testing the ontology. In this sense, these methods can be classified as black-box testing \cite{25} according to the classical definition in software engineering, since the definition of tests does not depend on the particular specification of knowledge proposed by the ontology. Black-box testing strategies have some disadvantages. For example, it is hard to determine the coverage level of a set of tests, since different black-box tests can repeatedly check the same portions of software. Further, the process of obtaining CQs is not automatic but creative \cite{11}. Depending on the size and complexity of the ontology, creating a suitable set of CQs is by itself a very challenging and costly task.

In this paper, we propose a new method for the (semi-)automatic creation of CQs that enables to evaluate the competency of SUMO-based ontologies. Our proposal is based on several predefined question patterns that yield to a large set of CQs by using information from WordNet \cite{9} and its mapping into SUMO \cite{27}. A preliminary version of our method for the automatic creation of CQs has been already presented in \cite{3}, where we also proposed an adaptation of the methodology for the evaluation of ontologies introduced in \cite{17} to be automatically applied using automated theorem provers (ATPs). For example, the synset \textit{schedule}$_{v}^{2}$ is related to \textit{schedule}$_{n}^{1}$ by the semantic relation \textit{result} in WordNet, as described in Figure \ref{fig:figure1}. In the same figure, we

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Creation of competency questions using WordNet}
\end{figure}

\begin{equation}
[\text{Planning}+] : \langle \textit{schedule}^{2}_{v} \rangle \xrightarrow{\langle \textit{result} \rangle} \langle \textit{schedule}^{1}_{n} \rangle : [\text{Plan}+]
\end{equation}

\begin{itemize}
  \item \textit{Planning}+
  \item \textit{schedule}^{2}_{v}
  \item \langle \textit{result} \rangle
  \item \textit{schedule}^{1}_{n}
  \item \text{Plan}+
\end{itemize}

\footnote{We denote WordNet synsets and relations between chevrons (angle brackets). Each synset (set of synonyms) refers to a word sense using the following format: \textit{word}$_{p}^{s}$, where}
also provide the mapping of schedule$^2$ and schedule$^1$ into SUMO, which are respectively connected to the meaning of Planning$^+$ and Plan$^+$. Using the above information, we obtain a new conjecture by stating the same fact in terms of SUMO: that is, “Plan is result of a process of Planning”. Indeed, we can propose two different conjectures (CQs) on the basis of the knowledge in Figure 1. In the first one, the statement is assumed to be true in the ontology:

$$\exists (?X ?Y)$$
$$\text{(and}$$
$$\text{($instance ?X Planning)}$$
$$\text{($instance ?Y Plan)}$$
$$\text{(result ?X ?Y)}))$$

In the second one, which is obtained by the negation of (1), we assume that the statement is false: that is, that “Plan is not result of any process of Planning”. By proceeding in this way, we obtain around 7,500 pairs of CQs on the basis of the information of WordNet using additional WordNet relations and question patterns.

The contributions of this paper are manyfold. First, we present an evolved version of our methodology for the evaluation of FOL ontologies using ATPs. As introduced in [3], our proposal is an adaptation of the methodology described in [17] for the design and evaluation of ontologies. Second, we propose a novel method for the (semi-)automatic creation of CQs that relies on a small set of question patterns. The proposed set of CQs enables the evaluation of a) the competency of ontologies derived from SUMO, b) the mapping between WordNet and SUMO, c) the knowledge in WordNet, and d) ATPs and other tools for automated reasoning. To the best of our knowledge, our proposal is the first attempt to exploit the information in WordNet and its mapping into SUMO for the automatic evaluation of knowledge-based resources using FOL ATPs. Third, we summarize the results of an automatic evaluation of the competency of several translations of SUMO into first-order logic (FOL)

$s$ is the sense number and $p$ is the part-of-speech ($n$ for nouns, $v$ for verbs and $a$ for adjectives). In addition, we denote the mapping information of each synset into SUMO separated by colon (:). For this purpose, SUMO concepts are denoted between square brackets and the symbol $+$ refers to the subsumption mapping relation.

Assuming that the knowledge in the ontology and WordNet is correct, and also that the mapping from WordNet to the ontology is correct, we consider that statement (1) is true according to our commonsense knowledge interpretation.
and the performance of various FOL ATPs by means of the adapted evaluation method proposed in [3]. Fourth, we also report on the evaluation of the set of resulting CQs according to different quality criteria. On one hand, we automatically check its level of coverage with respect to the evaluated ontologies by parsing the proofs provided by ATPs. On the other hand, we perform a manual evaluation of a sample of the CQs and analyse in detail its results by considering the accuracy of proposed conjectures, the mapping information of the involved synsets and the knowledge in the ontology.

Outline of the paper. In order to make the paper self-contained, in the next section we review the state-of-the-art in automatic evaluation of SUMO-based ontologies using CQs. Our revision includes the existing translations of SUMO into FOL, the most successful FOL ATPs and the previously proposed CQs. In Section 3 we describe our methodology for the automatic evaluation of ontologies using ATPs. Next, in Section 4 we introduce our proposal for the (semi-)automatic creation of CQs by exploiting the knowledge in WordNet and its mapping into SUMO with the purpose of evaluating SUMO-based ontologies. The different question patterns proposed for the creation of CQs are described in Sections 5-8. Then, we report on our experimental evaluation of the competency of some FOL translations of SUMO, the performance of FOL ATPs and the quality of the proposed CQs in Section 9. Finally, we give some conclusions and discuss future work in Section 10.

2. State of the art

In this section, we review the state-of-the-art in automatic evaluation of FOL ontologies. For this purpose, we focus on the description of the resources that have been proposed and used in the literature for the evaluation of SUMO-based ontologies using CQs. First, we introduce SUMO and its transformations into FOL in the following subsection. Next, we describe the most successful state-of-the-art FOL ATPs in Subsection 2.2. Finally, we review the CQs that have been previously proposed for the evaluation of SUMO-based ontologies in Subsection 2.3.

2.1. SUMO and its Transformations into FOL

SUMO[26] has its origins in the nineties, when a group of engineers from the IEEE Standard Upper Ontology Working Group pushed for a formal
ontology standard. Their goal was to develop a standard upper ontology to promote data interoperability, information search and retrieval, automated inference and natural language processing.

SUMO is expressed in SUO-KIF (Standard Upper Ontology Knowledge Interchange Format [29]), which is a dialect of KIF (Knowledge Interchange Format [13]). Both KIF and SUO-KIF can be used to write FOL formulas, but its syntax goes beyond FOL. Consequently, SUMO cannot be directly used by FOL ATPs without a suitable transformation [2].

The knowledge in SUMO is organized around the notions of object and class —the main SUMO concepts— by means of the meta-predicates $\text{instance}$ and $\text{subclass}$. SUMO objects and classes are not disjoint, since every SUMO class is defined to be instance of class and, thus, every SUMO class is also a SUMO object. Additionally, SUMO also differentiates relations and attributes. In particular, SUMO distinguishes between individual relation and attributes —that is, instances of the SUMO classes Relation and Attribute respectively— and classes of relations and attributes —that is, subclasses of the SUMO classes Relation and Attribute respectively. SUMO provides specific predicates for dealing with relations and attributes. Some of the most important ones are the next ones:

- $\text{subrelation}$, which relates two individual SUMO relations (that is, two instances of the SUMO class Relation).
- $\text{subAttribute}$, which relates two individual SUMO attributes (that is, two instances of the SUMO class Attribute).
- $\text{holds}^k$, which relates an individual SUMO relation (that is, an instance of the SUMO class Relation) with a $k$-tuple of SUMO concepts.

| Sumo | TPTP-SUMO v5.3.0 | TPTP-SUMO v2.2 | Adimen-SUMO v2.6 |
|------|-------------------|----------------|-----------------|
| Objects | 20,168 | 2,920 | 940 | 1,007 |
| Classes | 5,595 | 2,086 | 2,093 | 2,120 |
| Relations | 369 | 208 | 207 | 207 |
| Attributes | 2,181 | 68 | 67 | 66 |
| **Total** | **28,313** | **5,282** | **3,307** | **3,400** |

Table 1: Some figures about SUMO, TPTP-SUMO and Adimen-SUMO
• *attribute*, which relates a SUMO object with an individual SUMO attribute (that is, an instance of the SUMO class *Attribute*).

For simplicity, from now on we denote the nature of SUMO concepts by adding as subscript the symbols $o$ (SUMO objects that are neither classes nor individual relations nor individual attributes), $c$ (SUMO classes that are neither classes of relations nor classes of attributes), $r$ (individual SUMO relations), $a$ (individual SUMO attributes), $R$ (classes of SUMO relations) and $A$ (classes of SUMO attributes). For example: *YearDuration*$_o$, *Artifact*$_c$, *customer*$_r$, *HotTemperature*$_a$, *TransitiveRelation*$_R$ and *Breakability*$_A$.

There exist different proposals for converting large portions of SUMO into a FOL ontology. In [31], the authors report some preliminary experimental results evaluating the query timeout for different options when translating SUMO into FOL. Evolved versions of the translation described in [31] can be found in the *Thousands of Problems for Theorem Provers* (TPTP) problem library[^37] (hereinafter TPTP-SUMO), but have been not longer maintained since TPTP problem library version v5.3.0 (current TPTP version is v6.4.0). Following the line of [18], in [2] we use ATPs for reengineering around 88% of SUMO, obtaining Adimen-SUMO (v2.2). Both TPTP-SUMO and Adimen-SUMO inherits information from the top and the middle levels of SUMO (from now on, the *core* of SUMO), thus not considering the information from the domain ontologies.

In Table 1, we provide some figures comparing the explicit content of SUMO, TPTP-SUMO and Adimen-SUMO. In particular, the number of objects, classes, relations (both individual relations and classes of relations) and attributes (both individual attributes and classes of attributes) that are explicitly defined. The most significant difference between TPTP-SUMO and Adimen-SUMO is the number of explicitly defined objects, which is due to the fact that during the FOL transformation many objects that are implicitly defined in SUMO are explicitly introduced in TPTP-SUMO. On the contrary, the translation from SUMO into Adimen-SUMO is based on a small set of axioms, which provide the axiomatization of SUMO meta-predicates. Besides $\$instance_{r}$ and $\$subclass_{r}$ for the definition of objects and classes, some of these meta-predicates are $\$disjoint_{r}$ and $\$partition_{r}$. The axiomatization of these meta-predicates, which is essential for the transformation of SUMO knowledge into FOL formulas, cannot be directly inherited from SUMO (see [http://www.tptp.org](http://www.tptp.org))
The transformation also adds new axioms for a suitable characterization of SUMO types, variable-arity relations and $\textit{holds}^k$ predicates, which simulate the use of variable-predicates in FOL formulas. We are continuously evolving and improving Adimen-SUMO by solving some of the defects presented in SUMO. As result of this process, we have corrected more than 100 defective axioms in the current version of Adimen-SUMO (v2.6).

With respect to higher-order aspects of SUMO, an additional translation is required for enabling the use of SUMO by means of pure higher-order theorem provers [30].

2.2. FOL Automated Theorems Provers

The automatic application of methodologies based on CQs requires the use of ATPs. State-of-the-art ATPs for FOL are highly sophisticated systems that have been proved to provide advanced reasoning support to expressive ontologies. Since 1993, many researchers have used the Thousands of Problems for Theorem Provers (TPTP) problem library as an appropriate and convenient basis for ATP system evaluation [37], which becomes the de facto standard set of test problems for classical FOL ATP systems. The performance of ATP systems is evaluated every year in the CADE ATP System Competition (CASC) [32, 38] in the context of a set of problems chosen from the TPTP problem library and applying a specified time limit for each individual problem. Among the systems that have ever participated in CASC, we have selected the ones that are of special interest for reasoning with FOL ontologies, which are Vampire [33], E [35] and VanHelsing [20]. Next, we describe those systems and justify our selection.

On one hand, we have selected two of the most successful ATP systems in the CASC competition. The first one is Vampire [33], an ATP system for first-order classical logic which has been the winner of the FOF\(^5\) and LTB\(^6\) divisions in CASC during several years. Vampire implements the calculi of ordered binary resolution and superposition for handling equality, and it also implements the Inst-gen calculus. Vampire uses various standard redundancy criteria and implements several simplification techniques for pruning the search space, such as subsumption, tautology deletion, subsumption resolution and rewriting by ordered unit equalities. The reduction ordering is the

\(^5\)First-Order Form non-propositional theorems (axioms with a provable conjecture).
\(^6\)First-order form theorems from Large Theories, presented in Batches.
Knuth-Bendix Ordering. Since 2012, four different versions of Vampire have participated in CASC: v2.6, v3.0, v4.0 and v4.1. Vampire v2.6 is the CASC-J6 (2012), CASC-24 (2013) and CASC-J7 (2014) FOF division winner, and also the CASC-J6 (2012) LTB division winner. Vampire v3.0 obtained the 2nd place in the CASC-24 (2013) FOF division, but performing faster than the winner (Vampire v2.6), and has been used for the experimentation reported in [3]. Vampire v4.0 is the CASC-25 (2015) and CASC-J8 (2016) FOF and LTB divisions winner. In addition, Vampire v4.0 is also the CASC-25 FNT and EPR divisions winner. Finally, Vampire v4.1 is the CASC-J8 (2016) FNT and TFT divisions winner, and also achieved the 2nd place in the CASC-J8 (2016) FOF and LTB divisions.

The second system that we have selected is E [35], a theorem prover for full FOL with equality which consists of a (optional) clausifier for pre-processing full first-order formulae into clausal form, and a saturation algorithm implementing an instance of the superposition calculus with negative literal selection and a number of redundancy elimination techniques. Among other awards, E has been one of the top three ATP systems in the FOF division of CASC since 2012. E has also been used as a subcomponent by some other competitors in CASC. For its evaluation, we use E v1.9, which is the last version available at [http://www.eprover.org](http://www.eprover.org).

On the other hand, we have selected an ATP system that has only participated once in CASC: VanHelsing [20], which obtained the 4th position in CASC-J7 (2014) FOF division[11] This last ATP system is a fully automated proof checker for a subset of first-order problems tailored to a class of problems that arise in compiler verification. VanHelsing accepts input problems formulated in a subset of the TPTP language and is optimized to efficiently solve expression equivalence problems formulated in FOL. It is worth to mention that VanHelsing accepts all the axioms of TPTP-SUMO and Adimen-SUMO. An interesting feature of VanHelsing is that it provides graphical debugging help which makes the visualization of problems and localization of failed proofs much easier. This feature could be very useful for the debugging and maintenance of Adimen-SUMO, its mapping from Word-

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7 First-order form non-propositional Non-Theorems.
8 Effectively PROpositional clause normal form theorems and non-theorems.
9 Typed First-order Theorems.
10 Although E v2.0 has participated in CASC-J8 (2016).
11 VanHelsing v1.0 can be downloaded from [https://github.com/VanHElsing/VanHElsing](https://github.com/VanHElsing/VanHElsing)
Net and its linking with other information resources.

2.3. Available Competency Questions for SUMO

In this subsection, we review the CQs that have been proposed in the literature for the evaluation of SUMO-based ontologies. We classify those CQs into 2 sets, depending on the nature of its creation method.

On one hand, the first set consists of only 64 CQs that have been manually created (creative CQs). This set includes the 33 CQs belonging to the Commonsense Reasoning (CSR) domain of the TPTP problem library that are based on SUMO. For example, the next conjecture belonging to the CSR domain of the TPTP problem library

\[ (\forall \text{ORG1} \text{ORG2} \text{ORG3}) \]

\[ (\Rightarrow) \]

\[ (\text{and}) \]

\[ (\text{mother } \text{ORG1} \text{ORG2}) \]

\[ (\text{sibling } \text{ORG1} \text{ORG3}) \]

\[ (\text{mother } \text{ORG3} \text{ORG2}) \]

states that “siblings have the same mother” as follows: the mother of an organism \text{ORG3} is \text{ORG2} whenever \text{ORG2} is mother of some other organism \text{ORG1} such that \text{ORG1} and \text{ORG3} are sibling. In the past, the CSR domain was part of the set of eligible problems for the LTB division in CASC, but is not currently used. In addition, we have proposed 5 creative CQs in [2] and 26 creative CQs in [3]. For example, the conjectures “Plants do not suffer from headache” [2] and “Herbivores eat animals” [3]:

\[ (\Rightarrow) \]

\[ (\text{attribute } \text{OBJ Headache}) \]

\[ \text{not} \]

\[ (\text{instance } \text{OBJ Plant})) \]

\[ (\exists \text{HERBIVORE ANIMAL ?EATING}) \]

\[ (\text{and}) \]

\[ (\text{instance } \text{HERBIVORE Herbivore}) \]

\[ (\text{instance } \text{ANIMAL Animal}) \]

\[ (\text{instance } \text{EATING Eating}) \]

\[ (\text{agent } \text{EATING } \text{HERBIVORE}) \]

\[ (\text{patient } \text{EATING } \text{ANIMAL})) \]
Obviously, conjecture (3) is assumed to be true and conjecture (4) is assumed to be false according to commonsense knowledge.

On the other hand, the second set consists of the CQs that have been obtained by following a (semi-)automatized process (automatically generated CQs). To the best of our knowledge, this set exclusively consists of the 7,112 CQs proposed in [3], where we introduced a preliminary version of the method described in this paper for the exploitation of WordNet and its mapping into SUMO. Among other restrictions, we focused on synsets connected to SUMO classes, thus discarding many mapping information. The resulting set of CQs have been used for the automatic evaluation of ATP systems reported in [4]. We provide more details about this preliminary version of our proposal in Section 4.

3. Automatic Evaluation of FOL Ontologies using CQs

In this section, we summarize our adaptation of the methodology for the design and evaluation of ontologies introduced in [17] to be automatically applied using state-of-the-art ATPs, as initially proposed in [3].

In [17], the authors propose to evaluate the expressiveness of an ontology by proving completeness theorems w.r.t. a set of CQs. The proof of completeness theorems requires to check whether a given CQ is entailed by the ontology or not: that is, given an ontology \( \Phi \) and a conjecture \( \phi \), we have to decide if \( \Phi \models \phi \). For this purpose, in [3] we propose to use ATPs like Vampire [33], E [35] or VanHelsing [20] that work by refutation12 within some given execution-time and memory limits. Theoretically, if the conjecture is entailed by the ontology, then ATPs will eventually find a refutation given enough time (and space). However, theorem proving in FOL is a very hard problem, so it is not reasonable to expect ATPs to find a proof for every entailed conjecture \([19]\). Thus, if ATPs are able to find a proof for a conjecture \( \phi \) in an ontology \( \Phi \), then we know for sure that the corresponding CQ is entailed by \( \Phi \): that is, \( \Phi \models \phi \). On the contrary, if ATPs cannot find a proof, we do not know if (a) the conjecture is not entailed by the ontology (\( \Phi \not\models \phi \)) or (b) although the conjecture is entailed, ATPs have not been able to find the proof within the provided execution-time and memory limits (\( \Phi \models \phi \)).

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12The proof that a conjecture is entailed by an ontology consists in demonstrating that the formula resulting from the conjunction of the ontology and the negation of the conjecture is unsatisfiable.
Due to the semi-decidability problem of FOL, increasing the execution-time and memory limits is not a solution for conjectures that are not entailed. For the same reason, using other systems that do not work by refutation (for example, by model generation) is not a general solution.

Further, we also propose to divide the set of CQs into two classes: truth-tests and falsity-tests, depending on whether we expect the conjecture to be entailed by the ontology or not. An example of truth-test is conjecture (2) — “Siblings have the same mother”—, which belongs to the CSR domain of the TPTP problem library, because it is expected to be entailed. On the contrary, conjecture (4) — “Herbivores eat animals”—, which belongs to the set of CQs proposed in [3], is a falsity-test since it is not expected to be entailed by the ontology.

In order to overcome the problem of deciding whether CQs are entailed or not by the ontology using ATPs that work by refutation, we propose to classify CQs as either (i) passing, (ii) non-passing or (iii) unknown using the following criteria:

- If ATPs find a proof, then truth-tests are classified as passing since the corresponding conjectures are expected to be entailed, while falsity-tests are classified as non-passing, because the corresponding conjectures are expected not to be entailed. For example, ATPs easily prove that conjecture (2) is entailed by Adimen-SUMO v2.6, thus the truth-test is classified as passing.

- Otherwise, if no proof is found, then we classify both truth- and falsity-tests as unknown because we do not know whether the corresponding conjectures are entailed or not. For example, conjecture (4) is classified as unknown according to Adimen-SUMO v2.6.

As discussed for the example in Figure 1 truth- and falsity-tests can be interpreted as complementary conjectures. That is, given a truth-test $\phi$, one can propose its negation $\neg\phi$ as falsity-test, and vice versa. For example, the following truth-test — “Herbivores do not eat animals”— is obtained by the negation of (4):
Table 2: Evaluating FOL Ontologies Using ATPs

| Problem classification | Truth-test    | Falsity-test       | Assessment                                      |
|------------------------|---------------|--------------------|-------------------------------------------------|
| Solved                 | Passing (Φ |= φ) | Unknown (Φ |= ¬φ) | φ is redundant knowledge                        |
|                        | Unknown (Φ |= φ) | Non-passing (Φ |= ¬φ) | Φ is validated against φ                        |
|                        | Unknown (Φ |= φ) | Non-passing (Φ |= ¬φ) | Φ and φ are incompatible                        |
| Incompatible           | Unknown (Φ |= φ) | Non-passing (Φ |= ¬φ) | There is a defect in Φ                          |
|                        | Unknown (Φ |= φ) | Non-passing (Φ |= ¬φ) | Φ is inconsistent                                |
|                        | Unknown (Φ |= φ) | Non-passing (Φ |= ¬φ) | Is φ redundant?                                  |
|                        | Unknown (Φ |= φ) | Non-passing (Φ |= ¬φ) | Is there any defect in Φ?                        |

Conjecture (5) is classified as passing according to Adimen-SUMO v2.6. In the same way, we obtain a new falsity-test by negating conjecture (2). Hence, in general we can assume that any set of CQs that is used for the evaluation of FOL ontologies consists of complementary truth- and falsity-tests. Further, from now on we consider a truth-test φ and its negative counterpart ¬φ as a single problem consisting of two conjectures. For the sake of simplicity, we denote each problem by its truth-test. Thus, the truth-test of a problem φ is φ itself, and the falsity test of a problem φ is ¬φ.

In Table 2 we describe the evaluation of a FOL ontology Φ on the basis of a set of problems using ATPs. For each problem, we distinguish four cases. In the first cases, a problem φ is decided to be solved because ATPs find a proof for either its truth-test φ or its falsity-test ¬φ. If ATPs are able to prove Φ |= φ, then we know that the knowledge in φ is already included in the ontology and, consequently, we say that the problem φ is entailed by the ontology Φ. Otherwise, when ATPs prove Φ |= ¬φ, this reveals the existence
of a defect in the ontology since we assume that $\phi$ is true. Therefore, we say that the problem $\phi$ is incompatible with the ontology. In the last two cases, the problem $\phi$ remains unsolved. On one hand, if $\Phi$ is inconsistent then ATPs find a proof for its truth- and falsity-test, which are respectively classified as passing and non-passing. Since falsity-tests are obtained by the negation of truth-tests and a consistent formula cannot entail a formula and its negation, then we know for sure that $\Phi$ is inconsistent in this case. On the other hand, both the truth- and the falsity-test of a problem $\phi$ are classified as unknown because ATPs do not find any proof before running out of resources. Hence, we have no information for the evaluation of $\Phi$ according to the problem $\phi$ and, more concretely, we do not know whether:

- $\phi$ is new knowledge that could be included in $\Phi$ for improving the knowledge in the ontology.
- $\phi$ is either redundant —that is, $\Phi$ already entails $\phi$— or incompatible with $\Phi$ —that is, $\Phi \models \neg\phi$—, since ATPs cannot find a proof within the given resources of time and memory.

4. Automatic Creation of CQs Using WordNet

In this section, we introduce our proposal for the creation of problems by exploiting WordNet and its mapping into SUMO, as introduced with the example in Figure 1. Our proposal is a substantially evolved version of the method presented in [3]. Among other improvements, we now make use of the different mapping relation between WordNet and SUMO, that were equally treated in [3], and we are now able to exploit additional WordNet information. In addition, we have also improved the process of obtaining a mapping between WordNet and the core of SUMO. As a consequence, the set of CQs introduced in this work —which is different from the one introduced in [3]— enables a more fruitful exploitation of the knowledge in WordNet and its mapping into SUMO. As far as we know, our proposals are the first attempts to exploit WordNet for the evaluation of SUMO and, in general, for the evaluation of knowledge-based resources of this kind. In the next subsections, we first focus on the description of the knowledge and the hypothesis that are the basis of our proposal (Subsection 4.1). Then, we describe the method for obtaining a mapping from WordNet into Adimen-SUMO in Subsection 4.2. Finally, we introduce the method for the translation of WordNet knowledge into Adimen-SUMO statements in Subsection 4.3.
4.1. Exploiting WordNet and its Mapping into SUMO

WordNet [9] is a large lexical database where nouns, verbs, adjectives and adverbs are grouped into sets of synonyms (synsets), each expressing a distinct concept. Although superficially resembling a thesaurus, WordNet interlinks not just word forms but specific senses of words. Thus, the main relation in WordNet is synonymy, but synsets are interlinked by means of many conceptual-semantic and lexical relations. For example, the super-subordinate relations hyperonymy and hyponymy. We use some of those relations in WordNet as source for the creation of SUMO problems. More concretely:

- **Morphosemantic Links** [10], which are semantic relations between morphologically related verbs and nouns provided in the morphosemantic database. From the 14 proposed semantic relations, we use *agent*, *instrument*, *result* and *event*. The first three ones relate a process (verb) with its corresponding agent/instrument/result (noun), while *event* relates nouns and verbs referring to the same process. For example, the synsets *patent* and *patentee* are related by *agent*, *cool* and *cooler* are related by *instrument*, *schedule* and *schedule* are related by *result* (see Figure 1), and the synsets *kill* and *killing* are related by *event*.

- **Antonymy** and **similarity** relations, which are used to organize adjectives as follows: *antonymy* connects pairs of adjectives with opposite semantics, and each of these adjectives in turn is linked to semantically

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13 Available at [http://wordnetcode.princeton.edu/standoff-files/morphosemantic-links.xls](http://wordnetcode.princeton.edu/standoff-files/morphosemantic-links.xls)
comparable adjectives—called *satellites*—by *similarity*. For example, the adjectives $\text{hot}_a$ and $\text{cold}_a$ are related by *antonymy*, and the adjectives $\text{blistering}_a$, $\text{warming}_a$, $\text{torrid}_a$, $\text{heated}_a$ and $\text{tropical}_a$ are satellite of $\text{hot}_a$ (see Figure 2). In addition, *antonymy* is inherited by *similarity*, which enables to extend the set of pairs of adjectives related by *antonymy*. In the above example, each satellite of $\text{hot}_a$ (resp. $\text{cold}_a$) is antonym of $\text{cold}_a$ (resp. $\text{hot}_a$) and, further, is also antonym of each satellite of $\text{cold}_a$ (resp. $\text{hot}_a$), obtaining in this way a set of 36 antonym-pairs from the information in Figure 2. In addition, *antonymy* also relates nouns or verbs with opposite semantics. For example, $\text{natural\_object}_n^1$ and $\text{artifact}_n^1$ are related by the semantic relation *antonymy*.

In the future, we plan to exploit additional relations and knowledge provided by WordNet for the creation of CQs.

WordNet is linked with SUMO by means of the mapping described in [27]. This mapping connects synsets of WordNet to terms of SUMO using three relations: *equivalence*, *subsumption* and *instance*. *Equivalence* denotes that the related WordNet synset and SUMO concept are equivalent in meaning, whereas *subsumption* and *instance* indicate that the WordNet synset is subsumed by the SUMO concept or is an instance of the SUMO concept respectively. Additionally, the mapping also uses the complementaries of *equivalence* and *instance*. We denote mapping relations by concatenating the symbols ‘=’ (*equivalence*), ‘+’ (*subsumption*), ‘@’ (*instance*), ‘\^=’ (complementary of *equivalence*) and ‘\^+’ (complementary of *subsumption*) to the corresponding SUMO concept. For example, the synsets $\text{horse}_n^1$, $\text{education}_n^1$, $\text{zero}_a^1$, $\text{natural\_object}_n^1$ and $\text{dark}_a^1$ are connected to $\text{Horse}_c=\text{, EducationalProcess}_c+\text{, Integer}_c@\text{, Artifact}_c\^=\text{ and RadiatingLight}_c\^+\text{ respectively. WordNet v3.0 consists of 117,659 synsets: 82,115 nouns, 13,767 verbs, 18,156 adjectives and 3,621 adverbs. From the 82,115 noun synsets, 576 synsets are connected to more than one SUMO concept. Furthermore, 1 noun synset, 1,560 adjective synsets and 179 adverb synsets are not connected to any SUMO concept. All the remaining synsets are connected to a single SUMO concept.}

The above introduced semantic knowledge of WordNet and its SUMO mapping are exploited for the construction of CQs. Our proposal is based on

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14 Note that *instance* denotes the relation that is used in the mapping between WordNet and SUMO (for example, in $\text{Integer}_c@\text{), while }$*instance*$_c$ denotes the meta-predicate that is used in the axiomatization of SUMO.
the hypothesis that both WordNet statements and the mapping information are correct. Under this assumption, we propose different question patterns with two different purposes: our first purpose is to validate the mapping itself and the second purpose is the validation of the knowledge in the ontology according to the knowledge in WordNet. For the validation of the mapping information, we propose the following two problem categories:

- **Multiple mapping** pattern. This category of problems focuses on synsets that are connected to multiple SUMO concepts. Assuming that the mapping is correct, the truth-tests of the proposed problems state that the SUMO concepts connected to the same synset are compatible. Hence, its negations (falsity-tests) state that those SUMO concepts are not compatible, which implies that the mapping is necessarily wrong. In Section 5 we describe the single question pattern from which we obtain the problems belonging to this category.

- **Event** patterns. Verbs and nouns referring to the same process are related by *event*. Being the same process, we consider that both synsets should be mapped into the same SUMO concept and, if not, our hypothesis is that the mapping information is compatible. Following this hypothesis, for each pair of verb and noun related by *event* and connected to different SUMO concepts, we propose a new problem such that its truth-test states that those SUMO concepts are compatible (truth-test): that is, that the mapping is not necessarily wrong. Thus, the corresponding falsity-tests state that SUMO concepts connected to verbs and nouns related by *event* are not compatible and, thus, that the mapping is wrong. This category is divided into 3 subcategories, depending on the mapping relations that are used in *event* pairs. In Section 6 we describe in detail the different question patterns and provide some examples.

In the case of problems proposed for the validation of the knowledge in the ontology, for each WordNet statement we create a problem such that its truth-test states the same affirmation in terms of SUMO. Next, we describe the two main categories of problems with this purpose:

- **Antonym** patterns. In this category, problems are obtained from question patterns based on *antonymy* as follows: since *antonymy* relates adjectives with opposite semantics in WordNet, for each pair of antonym
adjectives we create a new problem such that its truth-test states that the SUMO concepts related to those adjectives are not compatible. Consequently, the corresponding falsity-tests state that the SUMO concepts related to antonym adjectives are compatible. Again, we propose 3 different subcategories depending on the mapping relations that are used in the pairs of antonym adjectives. This category is described in Section 7.

- Process patterns. This category consists in question patterns that focus on verbs and nouns related by agent, instrument and result, and the truth-tests of the proposed problems state the same relation in terms of SUMO. For example, conjecture (I) states that schedule\textsubscript{2} and schedule\textsubscript{1} are related by result, in terms of SUMO. The corresponding falsity-tests state that the SUMO concepts connected to synsets in agent/instrument/result pairs of verbs and nouns are not related in the same form. We propose a subcategory of problems for each relation and, in addition, a different question pattern for each possible combination of mapping relations. We provide a complete description of this category of problems in Section 8.

4.2. Obtaining a mapping between WordNet and the core of SUMO

The mapping between WordNet and SUMO uses terms from the core —top and middle levels— of SUMO, but also from the domain ontologies. However, both TPTP-SUMO and Adimen-SUMO only use axioms from the core of SUMO.

A full mapping between WordNet and the core of SUMO is obtained by means of the structural relations of SUMO: $\text{instance}_r$, $\text{subclass}_r$, $\text{subrelation}_r$, and $\text{subAttribute}_r$. Since $\text{subclass}_r$, $\text{subrelation}_r$, and $\text{subAttribute}_r$ are transitive and, additionally, the relations $\text{instance}_r$, $\text{subrelation}_r$, and $\text{subAttribute}_r$ are inherited through $\text{subclass}_r$, it is not difficult to obtain the super-concepts of each SUMO concept. By proceeding in this way, for each SUMO concept that is not defined in the core of SUMO we have obtained its set of most-specific super-concepts that are defined in the core of SUMO. If a SUMO concept is already defined in the core of SUMO, then its set of most-specific SUMO concepts defined in the core of SUMO exclusively consists of itself. Additionally, we have manually corrected some minor errors and typos affecting to 293 SUMO concepts. To sum up, 24,906 SUMO concepts not defined in the core of SUMO are used in the WordNet-SUMO mapping, from which
14,472 concepts are related with several (more than one) super-concepts belonging to the core of SUMO, whereas 10,434 concepts are related with a single super-concept.

Using the above described sets of most-specific super-concepts, we obtain the mapping between each synset $ws$ of WordNet and the core of SUMO as follows: if $ws$ is already mapped into a concept in the core of SUMO, we simply keep the current mapping of $ws$; otherwise, if $ws$ is connected to a concept $C$ that is not defined in the core of SUMO, then we map $ws$ to its set of most-specific super-concepts of $C$ in the core of SUMO. Additionally, in the latter case, the equivalence mapping relation is replaced with subsumption, since the super-concepts of $C$ are more general than $C$. For example, the synset $frying_1^n$ is connected to $Frying_c=$, which belongs to the domain ontology Food. In the same domain ontology, $Frying_c$ is defined to be subclass of $Cooking_c$, which is defined in the top level of SUMO. That is, $Cooking_c$ is defined in the core of SUMO, but $Frying_c$ is not defined in the core of SUMO, but $Cooking_c$ is. Thus, we decide to connect $frying_1^n$ to $Cooking_c$ in the mapping from WordNet to the core of SUMO. However, instead of equivalence, we connect $frying_1^n$ to $Cooking_c$ using the subsumption mapping relation: that is, $Cooking_c=$ (see Figure 3). It is worth to note that the complementaries of relations equivalence and subsumption are only used with concepts belonging to the core of SUMO in the WordNet-SUMO mapping.

As result of the above process, we obtain a mapping between all the synsets of WordNet and the core of SUMO except for 822 nouns, 24 verbs, 3,634 adjectives and 260 adverbs. In addition to the synsets that are not connected to any concept, this process also reveals the existence of synsets connected to concepts that were defined in older versions of SUMO but that are not longer available in the current one. For example, the synsets $salmon_1^n$ and $architect_2^n$ are respectively connected to $Salmon_c=$ and $Architect_c=$, which do not appear in the latest versions of SUMO. In total, 113 concepts that are

Figure 3: Obtaining a mapping between WordNet and Adimen-SUMO
used in the WordNet-SUMO mapping are not currently defined in the ontology. In order to obtain a whole mapping into the core of SUMO, all the synsets without a suitable mapping (around 4,700 synsets) are connected to the SUMO top-concept Entity, using subsumption: that is, Entity.+ . In the resulting mapping, 1,104 noun synsets and 2 verb synsets are connected to multiple SUMO concepts — the mapping of those synsets is used in the Multiple mapping category for the creation of CQs (see Section 5) —, whereas all the remaining ones are connected to a single concept.

4.3. Translating the mapping information into the language of SUMO

In order to use the WordNet-SUMO mapping for obtaining CQs, we have to characterize the mapping information using statements in the language of SUMO.

As described in Subsection 4.2, each WordNet synset is connected to SUMO concepts using equivalence, subsumption (or its complementaries) and instance. For example, the synsets horse\textsuperscript{1n}, pony\textsuperscript{1n} and Secretariat\textsuperscript{2n} are respectively connected to Horse\textsubscript{c}=, Horse\textsubscript{c}+ and Horse\textsubscript{c}@. Thus, in a literal (or strict) interpretation of the WordNet-SUMO mapping, horse\textsuperscript{1n} is exactly equivalent to the SUMO concept Horse, while pony\textsuperscript{1n} is subsumed by Horse and Secretariat\textsuperscript{2n} is instance of Horse. In order to translate the above interpretation of the mapping information into statements in the language of SUMO, we can simply use equality in the case of the synset horse\textsuperscript{1n}. With respect to the last two synsets, we can use the meta-predicates $\text{subclass}_r$ and $\text{instance}_r$, respectively. Likewise, since male\textsuperscript{1n} is connected to both Male\textsubscript{a}+ and Horse\textsubscript{c}+, we have that male\textsuperscript{1n} is subsumed by both Male\textsubscript{a} and Horse. Hence, by following the same literal interpretation of the mapping information, male\textsuperscript{1n} should be translated as both subclass of Horse —by means of $\text{subclass}_r$— and subattribute of Male —by means of $\text{subAttribute}_r$. However, this literal interpretation of the mapping information would lead to inconsistent SUMO statements: on one hand, $\text{subAttribute}_r$ relates two individual SUMO attributes, which are therefore restricted to be instance of Attribute; on the other hand, $\text{subclass}_r$ relates two SUMO classes, which are defined to be instance of class\textsubscript{c}. Since the SUMO classes Attribute\textsubscript{c} and class\textsubscript{c} are disjoint, it is inconsistent to state that any SUMO concept is both subclass of Horse and subattribute of Male\textsubscript{a}.

Unlike its literal interpretation, one can propose several suitable translations of the mapping information that do not yield to inconsistent SUMO statements. Among the existing options, in this work we use two different
translations of the mapping information on the basis of the following criteria. First, our main purpose is to exploit as much information as possible, in particular for obtaining the maximum amount of problems. Second, our intention is also to propose the strongest possible candidate truth-tests. It is worth to note that the above two criteria are sometimes opposite, so we need to find a trade-off between them.

Next, we introduce two different proposals for the translation of the mapping information into SUMO statements, where the second proposal produces stronger statements than the first one. The purpose of our first proposal is to relate WordNet synsets with a set of SUMO objects, while the purpose of the second one is to relate WordNet synsets with SUMO classes. For these purposes, we consider the nature of the SUMO concept to which a synset is connected in order to choose the most suitable SUMO predicate: either $equal$, $instance$, $subclass$, or $attribute$.

**First proposal.** In order to restrict the set of single SUMO objects that can be related with a given synset, we make use of a lenient interpretation of the WordNet-SUMO mapping. In the proposed SUMO statements, we use the predicate $equal$ with synsets connected to SUMO objects, the predicate $instance$ with synsets connected to SUMO classes and $attribute$ with synsets connected to SUMO attributes. We use a different variable in the SUMO statement proposed for each individual synset. The quantification of the introduced variables is determined by question patterns and the mapping relation that is used for connecting the given synset (see Sections 5 and 7). Next, we formalize our proposal for the translation of the mapping information of synsets connected to a single SUMO concept:

- If the given synset is connected to a **SUMO object**, then we simply use equality to state that the synset is exactly related with that SUMO object. For example, the synset $yearlong$ is connected to the SUMO object $YearDuration$, thus the statement

  $$(\text{equal} \ ?X \ YearDuration) \tag{6}$$

In this work, we do not translate the mapping information of synsets connected to SUMO relations. This information should be translated using $holds$. However, the arity of SUMO relations is greater than 1 and, consequently, $holds$ relates SUMO relations with tuples of 2 or more SUMO concepts. Therefore, it is not possible to determine which set of single SUMO concepts is related with a given synset by using $holds$. 

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is representing that the values of ?X related with yearlong\textsubscript{1} have to be equal to YearDuration\textsubscript{o}.

- If the synset is connected to a SUMO class, then we use the SUMO predicate $\textnormal{instance}_r$. For example, artifact\textsubscript{n} is connected to the SUMO class Artifact\textsubscript{c}, hence

\[(\textnormal{$\textnormal{instance}\ ?X\ Artifact})\]  

(7)

is stating that the values of ?X related with artifact\textsubscript{n} have to be instance of Artifact\textsubscript{c}.

- If the given synset is connected to an individual SUMO attribute, we can establish the properties of the SUMO objects related to that synset using the SUMO predicate attribute.\footnote{Due to the restrictions on arguments of predicates provided by SUMO domain axioms, we use property instead of attribute when convenient.} For example, goddess\textsubscript{n} is connected to Female\textsubscript{a} as stated before, therefore the statement

\[(\textnormal{attribute}\ ?X\ Female)}\]  

(8)

is stating that the values of ?X related with goddess\textsubscript{n} have Female\textsubscript{a} as property.

- Finally, if the synset is connected to a class of SUMO attributes, then we have to conveniently combine the SUMO predicates attribute and $\textnormal{instance}$. For example, the synset breakableness\textsubscript{1} is connected to BreakabilityAttribute\textsubscript{A}, which denotes a class of SUMO attributes. Hence, the statement

\[(\textnormal{exists}\ (?Z)\ (\textnormal{and} (\textnormal{$\textnormal{instance}\ ?Z\ BreakabilityAttribute}) (\textnormal{attribute}\ ?X\ ?Z))))\]  

(9)

is stating that the values of ?X related with breakableness\textsubscript{1} have some instance of BreakabilityAttribute\textsubscript{A} as property.

Regardless the nature of the SUMO concept to which a synset is connected, we negate the statements obtained for synsets connected using the
complementary of the equivalence or the subsumption mapping relations. For example, the synset $naturalObject^1_n$ is connected to $Artifact_c$. By proceeding as described above, we would obtain statement (7). Hence, we negate statement (7) and obtain
\[
\neg (\text{Instance } ?X \text{ Artifact})
\]
which states that the values of $?X$ related with $naturalObject^1_n$ cannot be instance of $Artifact_c$.

In addition, for the translation of the mapping information of synsets connected to more than one SUMO concept, we propose to conveniently combine the statements obtained for each single SUMO concept as stated before with conjunction. In this way, the mapping information of $male\_horse^1_n$, which is connected to both $Male_{a+}$ and $Horse_{c+}$, is translated as follows:
\[
\text{(and })
\]
\[
(\text{attribute } ?X \text{ Male})
\]
\[
(\text{Instance } ?X \text{ Horse})
\]

Second proposal. In this proposal for the translation of the mapping information, we obtain stronger statements by restricting the SUMO class —instead of the SUMO object— that is related with a given synset. Thus, we exclusively consider those synsets connected to SUMO concepts which are classes and discard the remaining ones. In the proposed SUMO statements, we simply use the predicates $equal_r$ —for synsets connected by equivalence— and $subclass_r$ —for synsets connected by subsumption or instance—. Therefore, the mapping information of synsets connected by the complementary of equivalence or subsumption is also discarded by the moment.

In the next sections, we use the above proposed methods for the translation of the mapping information of synsets in order to obtain CQs according to different conceptual question patterns. By following our previously introduced criteria, we use the first proposal in Sections 5 and 7-8, while the second one is used in Section 6. In those sections, we also discuss on the differences of using each of the proposed translations of the mapping information.

5. Multiple Mapping Pattern

In this section, we describe the problems that are obtained from synsets connected to several SUMO concepts for the validation of the mapping in-
Figure 4: Multiple mapping pattern: $\text{warhead}_n$.

formation.

For this purpose, we assume that both WordNet statements and the mapping information of synsets are correct. Under this assumption, from each synset connected to more than one SUMO concepts we propose a new problem such that its truth-test states that those SUMO concepts are compatible. Therefore, the corresponding falsity-tests state that the SUMO concepts connected to the same synset are not compatible, which contradicts our assumption. In both cases, we follow the first proposal for the translation of the mapping information described in Subsection 4.3. Our second proposal for the translation of the mapping information is not suitable since many synsets are connected to SUMO concepts which are not classes.

As described in Subsection 4.2, there are 1,106 synsets (1,104 nominal and 2 verbal) connected to more than one SUMO concepts as result of the process of obtaining a mapping from WordNet to the core of SUMO. Since equivalence is replaced with subsumption in that process, all the synsets are connected using subsumption or instance. Hence, in this category we propose a single question pattern for the creation of problems such that its truth-tests state that the SUMO concepts connected to a single synset are compatible. This simply implies to consider the variable used for the translation of the mapping information of synsets as existentially quantified.

For example, $\text{warhead}_n$ is connected to $\text{ExplosiveDevice}_{c+}$ and $\text{Weapon}_{c+}$ as described in Figure 4, from which we obtain the following truth-test that states that $\text{ExplosiveDevice}_{c}$ and $\text{Weapon}_{c}$ are compatible:

$$\exists X \left( \text{instance } X \text{ ExplosiveDevice} \land \text{instance } X \text{ Weapon} \right)$$

The corresponding falsity-test, which is obtained by negating (12), states that $\text{ExplosiveDevice}_{c}$ and $\text{Weapon}_{c}$ are not compatible. The mapping of $\text{warhead}_n$
is validated since ATPs are able to find a proof for (12) in Adimen-SUMO v2.6, but not in TPTP-SUMO and Adimen-SUMO v2.2. For example, ATPs are able to discover that \textit{Bomb}_c is subclass of both \textit{ExplosiveDevice}_c and \textit{Weapon}_c, thus any instance of \textit{Bomb}_c is also instance of \textit{ExplosiveDevice}_c and \textit{Weapon}_c simultaneously. Consequently, the proposed problem is decided to be solved and entailed in Adimen-SUMO v2.6, while it is unsolved in TPTP-SUMO and Adimen-SUMO v2.2.

Similarly, \textit{coal}^l_n is connected to both \textit{FossilFuel}^+_c, \textit{Mineral}^+_c and \textit{Rock}^+_c (see Figure 5). Hence, we create a new problem such that its truth-test states that \textit{FossilFuel}^+_c, \textit{Mineral}^+_c and \textit{Rock}^+_c are compatible:

\begin{verbatim}
(exists (?X)
    (and
        ($instance ?X FossilFuel)
        ($instance ?X Mineral)
        ($instance ?X Rock)))
\end{verbatim}

ATPs find a proof (as before, only in Adimen-SUMO v2.6) for the corresponding falsity-test, which is obtained by negating (13) and states that \textit{FossilFuel}^+_c, \textit{Mineral}^+_c and \textit{Rock}^+_c are not compatible: for example, ATPs are able to discover that every instance of \textit{FossilFuel}^+_c has \textit{Liquid}^+_a as attribute\footnote{Every instance of \textit{Solution}^+_c, which is a super-class of \textit{FossilFuel}^+_c, has \textit{Liquid}^+_a as attribute.} and every instance of \textit{Rock}^+_c has \textit{Solid}^+_a as attribute, being \textit{Liquid}^+_a and \textit{Solid}^+_a contrary attributes. Consequently, this falsity-test enables to detect a defect in the mapping information of \textit{coal}^l_n and the problem is decided to be solved and incompatible in Adimen-SUMO v2.6.

By proceeding in this way, we create 151 problems from the single question pattern proposed in this category.
6. Event Patterns

In this section, we describe the problems that are obtained from the question patterns based on the semantic relation \textit{event} defined in the \textit{Morphosemantic Links} database \cite{10} of WordNet for the validation of the mapping information of synsets.

For this purpose, besides assuming that WordNet statements and the mapping information of synsets are correct, we also assume that WordNet synsets related by \textit{event} should be connected to the same SUMO concept since \textit{event} relates verb and noun synsets referring to the same process. Under those assumptions, for each verb and noun synsets related by \textit{event} and connected to different SUMO concepts, we propose a new problem such that its truth-test states that the SUMO concepts linked to those synsets are compatible. Hence, the corresponding falsity-tests state that the SUMO concepts connected to verb and noun synsets related by \textit{event} are not compatible, which contradicts our assumptions.

In the \textit{Morphosemantic Links} database of WordNet, there are 8,158 event-pairs of synsets where the two synsets are equally mapped in 1,991 event-pairs. In addition, the synsets are connected to different SUMO concepts where at least one of them is not a SUMO class in only 499 event-pairs. Thus, we decide to apply our second proposal for the translation of the mapping information described in Subsection 4.3 in order to create problems on the basis of the remaining 5,668 event-pairs where the two synsets are connected to different SUMO classes. By proceeding in this way, we obtain stronger truth-tests than using our first proposal for the translation of the mapping information. In the next subsections, we introduce different conceptual patterns of questions depending on the used mapping relations.
6.1. Event Pattern #1

The first question pattern is focused on the 26 event-pairs where both synsets are connected to two different SUMO classes using equivalence. Since the mapping of those synsets exactly denotes the SUMO class to which the synset is related, our question pattern states that those SUMO classes are completely equivalent by using equality.

For example, the synsets kill$_c^1$ and killing$_n^2$ are related by event and respectively connected to the SUMO classes Death$_c^1$ and Killing$_c^2$, as described in Figure 6, from which we obtain the next truth-test:

$$(\text{equal Death Killing})$$  \hspace{1cm} (14)

The corresponding falsity-test, which is obtained by negating (14), states that Death$_c$ and Killing$_c$ are different. This falsity-test is classified as non-passing only in Adimen-SUMO v2.6: the patient of Killing$_c$ is restricted to be instance of Human$_c$, while any instance of Organism$_c$ can be the patient of Death$_c$. Consequently, the proposed problem is decided to be solved and incompatible in Adimen-SUMO v2.6. It is worth to note that in order to state the equivalence of the classes Death$_c$ and Killing$_c$ using our first proposal for the translation of the mapping information, we would have to state that the set of objects belonging to those classes are equal, which is a weaker affirmation than conjecture (14).

Using this first question pattern, we obtain 24 problems.

6.2. Event Pattern #2

In this subsection, we describe the question pattern that focuses on the 509 event-pairs where one synset is connected using equivalence, while the other synset is connected using instance or subsumption.
In this case, we know the precise SUMO class to which the synset connected by equivalence is related, as in the previous subsection. However, for the synset connected by subsumption or instance, we only know the superclass of the SUMO class to which that synset is related. That is, we know that the synset is connected to some subclass of the class provided in the mapping information. Hence, in order to prove that those SUMO classes are compatible, we have to demonstrate that the class related to the synset connected by equivalence is subclass of the class related to the synset connected by subsumption or instance.

For example, fix$_v^1$ and fixing$_n^1$ are related by event and connected to Pretending$_c+$ and Repairing$_c=$ respectively, as described in Figure 7. Therefore, we create a new problem such that its truth-test states that Repairing$_c$ is subclass of Pretending$_c$.

\[(\$subclass \text{Repairing Pretending})\] \hspace{1cm} (15)

and the corresponding falsity-test states that Repairing$_c$ cannot be subclass of Pretending$_c$. Conjecture (15) and its negation are not proved to be entailed by TPTP-SUMO or Adimen-SUMO in our experimentation.

From this second event pattern of questions, we obtain 350 problems.

6.3. Event Pattern #3

Finally, we focus on the 5,130 event-pairs where both synsets are connected using instance or subsumption.

In this case, we only know the superclass of the SUMO class to which each synset is related. Therefore, in order to prove that those SUMO classes are compatible, we have to demonstrate that those SUMO classes have some subclass in common.

For example, appraise$_v^1$ and appraisal$_n^1$ are related by event and respectively connected to Judging$_c+$ and Comparing$_c+$, as described in Figure 8.
From this event pair, we create a new problem such that its truth-test states that *Judging* and *Comparing* have some common subclasses:

\[
\text{(exists } (?X) \\
\text{ (and } \\
\text{ ($subclass ?X \text{ Judging}) \\
\text{ ($subclass ?X \text{ Comparing})))}
\]

Thus, the corresponding falsity-test states that *Judging* and *Comparing* do not have any common subclass. Conjecture (16) and its negation are not proved to be entailed by TPTP-SUMO or Adimen-SUMO in our experimentation.

Using this third question pattern based on *event*, we obtain 2,011 different problems.

### 7. Antonym Patterns

In this section, we describe the problems that are obtained from the question patterns based on antonyms for the validation of the knowledge in the ontology according to WordNet. For this purpose, we assume that both WordNet statements and its mapping into SUMO are correct. Under those assumptions, questions patterns focus on the *antonymy* —which relates words with opposite semantics— and *similarity* —that links semantically comparable words— relations of WordNet (see Figure 2) and propose to create new problems such that its truth-tests state that the SUMO objects related to antonym words are not compatible. Thus, the corresponding falsity-tests state that the SUMO objects related to antonym words are compatible.

WordNet provides 7,604 antonym-pairs, from which 1,950 are noun-pairs, 1,016 are verb-pairs, 3,998 are adjective-pairs and 640 are adverb-pairs. In addition, given a synset *ws* in an antonym-pair that is related with other synset *ws'* via similarity, we can propose a new antonym-pair by simple replacing *ws* with *ws'* in the pair. By proceeding in this way, we extend the given 7,604 antonym-pairs to a set of 121,496 antonym-pairs. Since many of the synsets in those pairs are connected to SUMO concepts which are not classes, we use our first proposal for the translation of the mapping information described in Subsection 4.3. Further, in 36,934 antonym-pairs some of the two synsets are mapped into SUMO relations and, therefore, those pairs have not been considered. In the remaining 84,562 antonym-pairs of synsets, there are:
• 186 antonym-pairs where both synsets are connected using *equivalence* (or its complementary).

• 2,542 antonym-pairs where *equivalence* (or its complementary) is mixed with *subsumption* (or its complementary) or *instance*.

• 81,834 antonym-pairs where both synsets are connected using *subsumption* (or its complementary) and *instance*.

In the following subsections, we describe 3 different question patterns depending on the used mapping relations.

7.1. Antonym Pattern #1

The first question pattern based on antonym is focused in the 186 antonym-pairs where both synsets are connected using *equivalence* (or its complementary). In this case, we assume that all the SUMO objects represented by the statement obtained from the first synset are incompatible with all the SUMO objects represented by the statement obtained from the second synset. Formally, this implies to consider the variables used in the SUMO statements proposed for the translation of the mapping information as universally quantified.

For example, the antonym-synsets $\text{birth}^2_n$ and $\text{death}^1_n$ are respectively connected to $\text{Birth}_c=$ and $\text{Death}_c=$ (see Figure 9), from which we obtain the following statements:

$$($$instance $?X \text{ Birth})$$ \hspace{1cm} (17) \\
$$($$instance $?Y \text{ Death})$$ \hspace{1cm} (18)

By considering $?X$ and $?Y$ as universally quantified, the following truth-test results from the combination of statements (17) and (18):
The above CQ states that any two SUMO objects that are instance of \textit{Birth} and \textit{Death} respectively are necessarily different. The corresponding falsity-test is obtained by negating (19), which states that there exists some SUMO object which is instance of \textit{Birth} and \textit{Death} at the same time.

From this question pattern, we obtain 71 different problems.

7.2. Antonym Pattern #2

The second question pattern is focused on the 2,542 antonym-pairs where equivalence (or its complementary) is mixed with subsumption (or its complementary) or instance. As in the previous case, we consider the variable in the SUMO statement proposed for the translation of equivalence mapping information as universally quantified. On the contrary, the variable in the SUMO statement translating subsumption or instance mapping information is considered as existentially quantified because the information provided by these mapping relations is weaker than the information provided by equivalence.

Since we are using both universally and existentially quantified variables, there are two additional options: we may nest the universally quantified statement inside the formula obtained from the existentially quantified statement, or nest the existentially quantified statement inside the formula that is
derived from the universally quantified statement. From these two options, we choose the one that yields stronger truth-tests, which is the first one. For example, the antonym synsets \textit{rural$_n^1$} and \textit{urban$_n^1$} are connected to \textit{GeographicArea$_c^+$} and \textit{City$_c^+$} respectively (see Figure 10), from which we obtain the following statements:

\begin{align*}
\text{(\$instance ?X GeographicArea)} \quad (20)
\text{(\$instance ?Y City))} \quad (21)
\end{align*}

Consequently, the SUMO statement that is obtained for the \textit{urban$_n^1$} is nested into the SUMO statement that is obtained for \textit{rural$_n^1$}:

\begin{align*}
\text{(exists (?X)} \quad (22)
\text{and}
\text{(\$instance ?X GeographicArea)}
\text{(forall (?Y)}
\text{(=>}
\text{(\$instance ?Y City)}
\text{(not}
\text{(equal ?X ?Y)))))}
\end{align*}

The above CQ states that there exists some SUMO object which is instance of \textit{GeographicArea$_c^+$} such that it is different from any SUMO object that is instance of \textit{City$_c^+$}. It is worth to note that if the previous statement holds, it implies that every SUMO object that is instance of \textit{City$_c^+$} is different from some SUMO object that is instance of \textit{GeographicArea$_c^+$}. In particular, all the SUMO objects that are instance of \textit{City$_c^+$} would be different from a single SUMO object that is instance of \textit{GeographicArea$_c^+$}. Hence, the truth-test in (22) is stronger than the conjecture that results by nesting the existentially quantified statement into the formula obtained from the universally quantified statement. Although \textit{City$_c^+$} is subclass of \textit{GeographicArea$_c^+$}, the truth-test defined in (22) is classified as passing only in Adimen-SUMO v2.6 since \textit{GeographicArea$_c^+$} has other subclasses that are disjoint with \textit{City$_c^+$}; for example, \textit{WaterArea$_c^+$}. Therefore, the proposed problem is decided to be solved and entailed in Adimen-SUMO v2.6.

To sum up, we obtain 489 problems from this second question pattern based on antonymy.

7.3. Antonym Pattern #3

In the third question pattern based on antonym, we focus on the 81,834 antonym-pairs where both synsets are connected using \textit{subsumption} (or its
complementary) and instance. As before, we consider the variables used in SUMO statements as existentially quantified, which implies to consider that some of the SUMO objects represented by the statements obtained from the mapping information of the antonym synsets are incompatible. For example, the antonym synsets $\text{stained}_a$ and $\text{unstained}_a$ are respectively connected to $\text{Coloring}_c^+$ and $\text{SurfaceChange}_c^+$ (see Figure 11), from which we obtain the following statements:

$$($$
$$\text{instance (?X Coloring)}$$
$$\text{not}$$
$$\text{instance (?Y SurfaceChanging))}$$
$$)$$

Therefore, we propose the following truth-test

$$\text{(exists (?X ?Y)}$$
$$\text{(and}$$
$$\text{($\text{instance (?X Coloring)}$$
$$\text{not}$$
$$\text{($\text{instance (?Y SurfaceChanging))}$$
$$\text{not}$$
$$\text{(equal ?X ?Y))))}$$

stating that there exist two different SUMO objects such that the first one is instance of $\text{Coloring}_c$ and the second one is not instance of $\text{SurfaceChanging}_c$. The corresponding falsity-test that is obtained by negating (25) states that any two SUMO objects such that the first one is instance of $\text{Coloring}_c$ and the second one is not instance of $\text{SurfaceChanging}_c$ are equal.

Using this third question pattern, we obtain 2,444 problems.

8. Process Patterns

In this section, we describe the problems that are obtained from the Morphosemantic Links database [10] of WordNet for the validation of the
knowledge in the ontology. As in the case of the question patterns based on antonym, we assume that both WordNet statements and its mapping into SUMO are correct.

Among the 14 semantics relations between morphologically related verbs and nouns provided by the Morphosemantic Links, we concentrate on agent, instrument and result, which relate a process (verb) with its corresponding agent/instrument/result (noun). For each pair of synsets connected by the above relations, we propose to create a new problem such that its truth-test states the same affirmation in terms of SUMO. For this purpose, we properly use the SUMO relations agent$_r$, instrument$_r$ and result$_r$ that link SUMO processes (i.e., an instance of the SUMO class Process) to its corresponding agent, instrument and result, which are respectively restricted to be an instance of the SUMO classes Agent$_c$, Physical$_c$ and Entity$_c$. That is, the SUMO relations agent$_r$, instrument$_r$ and result$_r$ connect two SUMO objects. Consequently, it is not feasible to use our second proposal for the translation of the mapping information described in Subsection 4.3, since the connected concepts are not SUMO classes. Depending on the mapping relations that are used to relate the verb and noun synsets, we next introduce 4 different question patterns by means of our first proposal for the translation of the mapping information.

In the Morphosemantic Links database, there are 5,295 relation-pairs of synsets where some of the relations agent, instrument and result is used. Among those pairs, there are 5,098 relation-pairs such that none of the synsets are connected to a SUMO relation and, additionally, none of the synsets is connected using the complementary of equivalence or subsumption. Therefore, we use those 5,098 relation-pairs for the creation of problems.

For example, the synsets instruct$_v^1$ and instructor$_n^1$ are related by agent and respectively connected to EducationalProcess$_c=$ and Teacher$_a=$ (see Figure 12). From the mapping information of those synsets, we obtain the following statements:

\[
\text{EducationalProcess}_c = \langle \text{instruct}_v^1 \rangle \xrightarrow{\text{agent}} \langle \text{instructor}_n^1 \rangle : \text{[Teacher}_a = ]
\]
Thus, we have to combine the above statements using the SUMO relation `agent` and quantify its variables in order to create a problem. However, unlike in the case of event question patterns, we cannot consider both variables in SUMO statements as universally quantified when both synsets are connected by equivalence (see Subsection 6.1): in our example, it is not true that all the SUMO objects with Teacher as attribute are the agent of all the instances of EducationalProcess. At most, we can state that all the instances of EducationalProcess have a SUMO object with the attribute Teacher as agent and, at the same time, all the SUMO objects with Teacher as attribute are the agent of some instance of EducationalProcess, as proposed in the next conjecture (truth-test):
Figure 14: Process pattern: verb and noun synsets connected by subsumption/instance and equivalence respectively

\[
\text{(and) (forall (\?X)}
\text{ (=>)}
\text{ ($\text{instance } \?X \text{ EducationalProcess})}
\text{ (exists (\?Y)}
\text{ (and)}
\text{ (attribute \?Y Teacher) (agent \?X \?Y))))}
\text{ (forall (\?Y)}
\text{ (=>)}
\text{ (attribute \?Y Teacher) (exists (\?X)}
\text{ (and)}
\text{ ($\text{instance } \?X \text{ EducationalProcess}) (agent \?X \?Y))))}
\]

The corresponding falsity-test states that either there exists some instance of \(\text{EducationalProcess}\) where its agent does not have \(\text{Teacher}\) as attribute or there exists some SUMO object with \(\text{Teacher}\) as attribute that it is not the agent of any \(\text{EducationalProcess}\).

Next, we summarize the proposed question patterns and the amount of problems that result from them. However, the resulting problems are organized into 3 categories — Agent, Instrument and Result — depending on the semantic relation with the purpose of analysing the knowledge in SUMO about each of these relations:

- The first question pattern focuses on relation-pairs where both synsets are connected by \textit{equivalence}, as the example in Figure 12. From this
Figure 15: Process pattern: verb and noun synsets connected by \textit{subsumption/instance}

pattern, we obtain 13 problems where 2 problems belong to the Agent category, 3 problems to the Instrument category and 8 problems to the Result category.

• The second question pattern focuses on relation-pairs where the verb synset is connected by \textit{equivalence} and the noun synset is connected by \textit{subsumption} or \textit{instance}, as the example in Figure 13. The truth-tests of the proposed problems state that all the SUMO objects that can be assigned to the verb synset have some of the SUMO objects that can be assigned to the noun synset as agent/instrument/result, which corresponds to the first half of the problem proposed by the first process question pattern (see conjecture (28)). Using this question pattern, we obtain 197 problems, from which 137, 30 and 30 problems respectively belong to the Agent, Instrument and Result categories.

• The third question pattern is focused on relation-pairs where the verb synset is connected by \textit{subsumption} or \textit{instance}, while the noun synset is connected by \textit{equivalence}, as the example in Figure 14. In this case, the truth-tests of the proposed problems state that all the SUMO objects that can be assigned to the noun synset are the agent/instrument/result of some SUMO object that can be assigned to the verb synset, which corresponds to the second half of the problem proposed by the first process question pattern (see conjecture (28)). Using this third question pattern, we obtain 137 problems, from which 27, 28 and 82 problems respectively belong to the Agent, Instrument and Result categories.

• The last question patterns is focused on relation-pairs where both the verb and noun synsets are connected by \textit{subsumption} or \textit{instance}, like the example in Figure 15. The truth-tests of the proposed problems state that some of the SUMO objects that can be assigned to the verb
synset have some of the SUMO objects that can be assigned to the noun synset as agent/instrument/result. From this question pattern, we obtain 1,618 problems, from which 663 problems belong to the Agent category, 287 problems to the Instrument category and 668 problems to the Result category.

In total, we obtain 829 problems for the Agent category, 348 problems for the Instrument category and 788 problems for the Result category.

9. Experimentation

On the basis of the set of CQs proposed in the above sections, we have performed several experiments in order to evaluate the competency of SUMO based ontologies and the performance of FOL ATPs by following the methodology described in Section 3. In this experimentation, we have used an Intel® Xeon® CPU E5-2640v3@2.60GHz with 2GB of RAM memory per processor. For each CQ, we provide an ontology and the given conjecture as input to the ATP system. In the next subsections, we report on the results of these experiments. Additionally, we have manually analysed some of the test in order to evaluate the proposed CQs, as reported in the last subsection.

9.1. Evaluating the competency of SUMO based ontologies

In this subsection, we report on the evaluation of the competency of TPTP-SUMO [31] and Adimen-SUMO [2]. In the case of Adimen-SUMO, we also evaluate the improvement between two different versions: Adimen-SUMO v2.2, which is the first version we proposed, and Adimen-SUMO v2.6.

Table 3 sums up some result figures of the ATP Vampire v3.0[33] when evaluating TPTP-SUMO and Adimen-SUMO (v2.2 and v2.6) with an execution time limit of 600 seconds. The election of Vampire v3.0 is based on the fact that it is the most successful ATP system in the experimentation reported in [4] when using the set of CQs proposed in [3] for the evaluation of ATPs. For each ontology, we provide the number (○ column) and percentage (○ column) of CQs that have been successfully proved together with the average run time (★ column).

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18 The ontology Adimen-SUMO, the set of CQs and all the execution reports are freely available at http://adimen.si.ehu.es.
19 http://www.vprover.org
| Problem category | TPTP-SUMO v5.3.0 | Adimen-SUMO v2.2 | Adimen-SUMO v2.6 |
|------------------|------------------|------------------|------------------|
|                  | ○ ○ ○ | ○ ○ ○ | ○ ○ ○ |
| Truth-tests      |                  |                  |                  |
| Multiple Mapping (151) | 0 - - | 0 - - | 23 15.23% |
| Event #1 (24) | 0 - - | 0 - - | 83 23.71% |
| Event #2 (350) | 82 23.43% | 83 23.71% | 68 23.71% |
| Event #3 (2,011) | 580 28.84% | 580 28.84% | 582 28.94% |
| Mapping (2,536) | 002 26.10% | 666 26.14% | 668 27.15% |
| Antonym #1 (71) | 12 16.90% | 24 33.80% | 44 61.97% |
| Antonym #2 (489) | 66 13.50% | 133 27.20% | 131 37.43% |
| Antonym #3 (2,444) | 83 3.40% | 213 8.70% | 231 9.07% |
| Agent (829) | 4 0.48% | 7 0.84% | 39 4.70% |
| Instrument (348) | 1 0.29% | 1 0.29% | 3 0.57% |
| Result (788) | 0 0.04% | 1 0.13% | 3 0.36% |
| Competency (4,969) | 170 3.42% | 325 6.54% | 357 7.23% |
| Total (7,505) | 832 11.09% | 988 13.16% | 1,805 24.05% |
| Falsity-tests    |                  |                  |                  |
| Multiple Mapping (151) | 1 0.66% | 3 1.99% | 2 1.32% |
| Event #1 (24) | 0 - - | 1 4.17% | 7 29.17% |
| Event #2 (350) | 0 - - | 27 7.71% | 131 37.43% |
| Event #3 (2,011) | 0 - - | 646 32.12% | 141 40.12% |
| Mapping (2,536) | 1 0.04% | 14 0.57% | 14 0.57% |
| Antonym #1 (71) | 0 - - | 1 1.41% | 4 5.63% |
| Antonym #2 (489) | 25 5.11% | 23 4.70% | 21 4.29% |
| Antonym #3 (2,444) | 13 0.53% | 14 0.57% | 1 0.04% |
| Agent (829) | 5 0.60% | 7 0.84% | 11 1.40% |
| Instrument (348) | 0 - - | 2 0.57% | 1 0.29% |
| Result (788) | 3 0.38% | 12 1.52% | 11 1.40% |
| Competency (4,969) | 46 0.93% | 54 1.09% | 41 0.83% |
| Total (7,505) | 47 0.63% | 85 1.13% | 827 11.02% |
| Total (15,010) | 879 5.85% | 1,073 7.14% | 2,632 17.53% |

Table 3: Evaluating the competency of SUMO ontologies using Vampire v3.0

From the results of problems proposed for the validation of ontologies, it is clear that Adimen-SUMO v2.6 outperforms TPTP-SUMO and Adimen-SUMO v2.2 in terms of competency in both the truth-test—more passing tests (1,117 against 170 and 325), since conjectures are expected to be entailed— and the falsity-test categories—less non-passing tests (41 against 46 and 54), since conjectures are expected not to be entailed—. Further, Adimen-SUMO v2.6 is by far the most competent ontology in all the validation subcategories of the truth-test categories. At the same time, Adimen-SUMO v2.2 clearly outperforms TPTP-SUMO in all the validation subcategories of the truth-test categories.

With respect to the validation of the mapping information, Adimen-SUMO v2.6 slightly outperforms TPTP-SUMO and Adimen-SUMO v2.2 in the truth-test category—more passing tests (668 against 662 and 663)—because there is almost no difference in the Event subcategories. On the
contrary, no proof is found for the truth-test Multiple Mapping subcategory using TPTP-SUMO or Adimen-SUMO v2.2, while 23 truth-tests can be classified as passing using Adimen-SUMO v2.6. In the case of falsity-tests, the difference is clearly larger: 786 non-passing tests using Adimen-SUMO v2.6 against 1 non-passing test using TPTP-SUMO and 31 non-passing tests using Adimen-SUMO v2.2. This result reveals that Adimen-SUMO v2.6 enables the detection of many defects in the mapping information which are not discovered using TPTP-SUMO or Adimen-SUMO v2.6.

Regarding efficiency, the average run times of Adimen-SUMO are in general shorter than the ones of TPTP-SUMO, especially in the truth-test categories: 14.68 s. (Adimen-SUMO v2.2) and 32.25 s. (Adimen-SUMO v2.6) against 44.19 s. (TPTP-SUMO). At the same time, the average run times of Adimen-SUMO v2.6 are longer than the ones of Adimen-SUMO v2.2. This fact leads us to think that the problems that are only solved using Adimen-SUMO v2.6 require complex and long proofs and, additionally, it also confirms the improvement of Adimen-SUMO v2.6 in terms of competency.

9.2. Evaluating the performance of FOL ATPs

According to the results reported in the previous section, the conjectures in the truth-test subcategories for the validation of the mapping information do not enable a suitable evaluation of ATPs since most of the proofs are obtained in less than 2 seconds (all the proofs from the truth-test subcategories). At the same time, very few CQs of the falsity-test subcategories for the validation of ontologies are proved (less than 1% of CQs). Consequently, we concentrate on the truth-test subcategories for the validation of ontologies and the falsity-test subcategories for the validation of the mapping information in order to evaluate FOL ATPs.

In Table 4, we sum up some figures of the evaluation of the different versions of Vampire (VP), E (EP) and VanHelsing (VH) introduced in Subsection 2.2 using Adimen-SUMO v2.6. For each ATP, we provide the number of proofs (column) and the average run times (column) in each problem subcategory.

Globally, Vampire v2.6 is the winner according to the total number of proofs (2,327 proofs) with a difference of 424 and 1,070 proofs to Vampire v3.0 (second place) and Vampire v4.1 (third place) respectively. This result

\[20\text{VanHelsing does not provide final run time.}\]
is different from our preliminary evaluation of ATPs reported in \cite{4}. In that evaluation, Vampire v3.0 was the most successful ATP and Vampire v2.6 nearly obtained the same number of proofs for the set of CQs proposed in \cite{3}, which is different from the set of CQs introduced in this work. With respect to the remaining ATPs (Vampire v4.0, E v1.9 and VanHelsing v1.0), the number of proofs is clearly smaller.

Regarding each problem subcategory, Vampire v2.6 is the winner in the truth-test problem category (1,556 proofs) and also in all the truth-test problem subcategories. On the contrary, Vampire v3.0 is the winner in the falsity-test problem category (786 proofs) and also in all the Antonym problem subcategories. In the case of the falsity-test problem subcategory, the differences between the two first ATPs (Vampire v3.0 and v2.6) are smaller than the differences between the two first ATPs in the truth-test problem subcategory (Vampire v2.6 and v4.1), but the difference between the two first ATPs and the remaining ones is clearly larger.

The analysis of efficiency is more disparate:

- Vampire v3.0 is the ATP with the lowest average run time (39.54 s.) followed by Vampire v4.0 (81.56 s.) and Vampire v2.6 (107.86 s.). However, Vampire v4.0 proves really few CQs in comparison with Vampire v2.6, which in general outperforms Vampire v4.0 in terms of efficiency except for the third problem subcategory of Antonym (182.29 s. against 60.32 s.) and the Multiple Mapping subcategory (271.55 s. against 55.36 s.).\footnote{The average run time in the first problem subcategory of Antonym is almost equal.}

\begin{table}[h]
\centering
\begin{tabular}{|l|c|c|c|c|c|c|c|}
\hline
Problem category & VP v2.6 & VP v3.0 & VP v4.0 & VP v4.1 & EP v1.9 & VH v1.0 \\
\hline
Antonym #1 (71) & 44 & 68.32 s. & 44 & 103.42 s. & 37 & 68.15 s. & 43 & 30.07 s. & 40 & 33.7 9 s. & 38 & - s. \\
Antonym #2 (489) & 204 & 86.84 s. & 193 & 77.22 s. & 54 & 130.27 s. & 119 & 144.33 s. & 126 & 93.60 s. & 112 & - s. \\
Antonym #3 (2,444) & 1,086 & 182.29 s. & 686 & 46.36 s. & 431 & 60.32 s. & 851 & 194.7 4 s. & 256 & 326.82 s. & 91 & - s. \\
Agent (829) & 43 & 14.93 s. & 39 & 6.28 s. & 10 & 22.94 s. & 23 & 318.42 s. & 7 & 254.54 s. & 3 & - s. \\
Instrument (348) & 61 & 3.36 s. & 61 & 45.61 s. & 25 & 64.65 s. & 26 & 404.10 s. & 1 & 71.68 s. & 1 & - s. \\
Result (788) & 118 & 4.46 s. & 94 & 11.04 s. & 52 & 74.86 s. & 64 & 294.91 s. & 7 & 107.13 s. & 6 & - s. \\
Truth-tests (4,969) & 1,556 & 141.43 s. & 1,117 & 49.53 s. & 609 & 67.80 s. & 1,126 & 196.18 s. & 437 & 227.49 s. & 251 & - s. \\
Multiple Mapping (151) & 3 & 271.55 s. & 2 & 230.74 s. & 2 & 55.36 s. & 3 & 85.13 s. & 0 & - s. & 0 & - s. \\
Event #1 (24) & 5 & 128.66 s. & 7 & 42.40 s. & 3 & 388.45 s. & 4 & 250.19 s. & 4 & 325.01 s. & 1 & - s. \\
Event #2 (350) & 117 & 58.43 s. & 131 & 36.53 s. & 38 & 173.34 s. & 41 & 88.12 s. & 52 & 305.14 s. & 15 & - s. \\
Event #3 (2,011) & 646 & 35.05 s. & 646 & 22.27 s. & 104 & 120.23 s. & 83 & 62.00 s. & 190 & 274.68 s. & 17 & - s. \\
\hline
\end{tabular}
\caption{Evaluating the performance of FOL ATPs}
\end{table}
Table 5: Evaluating the competency of Adimen-SUMO v2.6

- Vampire v2.6 is the ATP with the third lowest average run time in the falsity-test problem subcategory, but outperforms Vampire v3.0 in terms of efficiency in 3 falsity-test problem subcategories (Antonym #1, Instrument and Result) while solving more CQs than the remaining ATPs.

- Vampire v4.1 and E v1.9 are the ATPs with the two worst average run times, but performing extremely well in the first subcategory of Antonym problems (Antonym #1). It is also worth to remark that the average run time of Vampire v4.1 in the Multiple Mapping problem subcategory is clearly the lowest one.

To sum up, we can conclude that our set of proposed CQs is really heterogeneous, enabling to evaluate a wide range of features of state-of-the-art ATPs.
9.3. Evaluating Adimen-SUMO v2.6 and its Mapping from WordNet

Finally, we evaluate the competency of Adimen-SUMO v2.6, which consists of 7,437 axioms: 4,638 unit clauses (atomic formulas) and 2,799 general clauses (non-atomic formulas). For this purpose, all the ATP systems introduced in the above subsection have been individually used to experiment with the whole set of 15,010 CQs and then the outputs obtained from them have been jointly analysed.

In Table 5, we report the results of this experimentation and our joint analysis. These results are organized in three main categories —Proofs, Coverage and Difficulty—, each of them consisting of three columns. In the first category (Proofs), we provide the number (◦ column) of CQs that are proved by some of the ATPs, together with its percentage (⋄ column) and the average run time (⋆ column). In the second category (Coverage), we provide the following figures about the axioms that are used in some of the proofs provided by ATPs:

- The number (N column) and percentage (P column) of used axioms.
- The number of different axioms that are exclusively used in proofs of the corresponding problem subcategory (E column).
- The number of used unit clauses (UC column) and general clauses (GC column).

In the last category (Difficulty), we provide a measure of how difficult is to prove each CQ by reporting the average number of different axioms (N column) that are used in each proof and, in particular, the average number of different unit clauses (UC column) and general clauses (GC column).

From the results reported in Tables 4 and 5, we can conclude that ATPs are able to prove different subsets of CQs. In this sense, the number of truth-tests proposed for the validation of ontologies that are proved by at least one of the ATPs (1,666 truth-tests) is 7.07% larger than the number of truth-tests that are proved by Vampire v2.6 (1,556 truth-tests), which is the most successful ATP. It is in particular the case of the second Antonym truth-test subcategory, where 233 tests are proved by some of the ATPs while each ATP at most proves 204 tests. Therefore, the number of CQs entailed by Adimen-SUMO could be larger than the number of proofs reported in Table 5. In particular, we could enlarge the number of proofs in our experiments by
increasing the execution time and memory limit settings or by tuning ATPs to Adimen-SUMO.

According to the results obtained in the problem categories proposed for the validation of the ontology and its alignment to WordNet (4,969 problems), we can conclude that:

- The knowledge of Adimen-SUMO and WordNet is well-aligned for 33.53% of problems (1,666 truth-tests from the Antonym and Relation problem subcategories are solved). In particular, 1,822 different axioms of the ontology (24.50% of the total) are used for the validation of the ontology.

- Only 1.19% of problems (59 falsity-tests from the Antonym and Relation problem subcategories are proved) enable to detect some failure or misalignment in the knowledge of Adimen-SUMO and WordNet, which involve a total of 199 axioms (2.68% of the total).

- The knowledge about incompatible classes and attributes in Adimen-SUMO is better covered by WordNet than the knowledge about the relations $\text{agent}_r$, $\text{instrument}_r$ and $\text{result}_r$: 48.07% of truth-tests from the Antonym subcategory (1,444 proofs from 3,004 CQs) are proved against 11.30% of truth-tests from the Relation subcategory (222 proofs from 1,965 CQs).

Besides evaluating the competency, incompatible (its falsity-test is classified as non-passing) and unsolved problems (both tests are classified as unknown) provide useful information to improve the ontology. For example, ATPs do not find a proof for the CQ in (19) (truth-test) and its negation (falsity-test). By inspecting the ontology, it is easy to check that the SUMO classes $\text{Birth}_c$ and $\text{Death}_c$ are not axiomatized to be disjoint, as one would naturally expect. Thus, the problem consisting of (19) (truth-test) and its negation (falsity-test) enables to detect a defect in the ontology.

With respect to quality, we can state that the problems proposed for the validation of the ontology are suitable for the evaluation of the competency of Adimen-SUMO on the basis of three indicators:

- The average run time of ATPs when solving a problem is longer than 10 seconds except for the Instrument and Result problem subcategories of truth-tests and the first subcategory of Antonym problems (Antonym #1) of falsity-tests.
• The average number of different axioms that are used in each proof (Difficulty columns in Table 5) is higher than 11 except for the case of the first Antonym subcategory (both truth- and falsity-tests) and the second Antonym subcategory of falsity-tests.

• There is a linear relation between the number of proofs (o column) and the number of different axioms that are used in proofs (Coverage columns). In addition, among the 921 axioms that are exclusively used in a single problem subcategory (E column), 803 axioms correspond to truth-test subcategories of problems proposed for the validation of the ontology.

As conclusion, the two first indicators lead us to affirm that the proofs for the problems in the Antonym and Relation subcategories are not trivial, while the last one reveals that ATPs are not repeatedly using a small subset of axioms of the ontology for constructing the proofs.

Regarding the validation of the mapping information, we have proposed 2,536 problems, from which 1,505 have been successfully solved by ATPs (59.35%): 717 truth-tests, which validate the mapping information of synsets, and 788 falsity-tests, which enable to detect defects in the mapping information of synsets. For example, the synsets $affirm^3_v$ and $affirmation^2_n$ are related by $event$ and respectively connected to $Communication_{+}$ and $Stating_{=}$, from which we obtain the following truth-test:

($\text{subclass Stating Communication}$)

The above CQ is entailed by Adimen-SUMO v2.6 since $Stating_{=}$ is subclass of $LinguisticCommunication_{+}$, which is in turn subclass of $Communication_{c}$. Therefore, the problem is decided to be solved and entailed, and we can conclude that the mapping of the synsets in the pair $event(affirm^3_v, affirmation^2_n)$ is validated according to our criteria. On the contrary, we detect some defect in the mapping information of the synsets in $event(represent^{14}_{v}, representation^{1}_{n})$ as follows. Since $represent^{14}_{v}$ and $representation^{1}_{n}$ are respectively connected to $Stating_{=}$ and $Imagining_{=}$, we propose the following falsity-test stating that its mapping is wrong:

($\text{not (equal Stating Imagining)}$)

ATPs can prove that the above CQ is entailed by Adimen-SUMO v2.6 since $Stating_{=}$ is subclass of $IntentionalProcess_{c}$ and $Dreaming_{=}$ is subclass of
### Imagining, IntentionalProcess, and Dreaming

The problem is decided to be solved and incompatible and it enables to detect that the mapping of (some of) the synsets in the pair `event(represent_v, representation_u)` is wrong.

#### 9.4. A Complete Analysis of a Small Set of Problems

As we have already described in the above subsections, the proposed set of CQs is suitable for evaluating the competency of Adimen-SUMO and for detecting some mapping failures. Additionally, there are some good indicators of the quality of the proposed CQs. However, a more detailed analysis of the quality of the proposed CQs and the mapping between WordNet and Adimen-SUMO requires a manual inspection of the conjectures, the mapping of the involved synsets and the proofs obtained by ATPs. Thus, we have randomly selected a sample of 75 problems (1%) following a uniform distribution.

In Table 6, we sum up some figures of our detailed analysis of the selected set of problems in four main categories —Problems, Mapping, Solutions and Missing solutions. In the first category (Problems), we provide the number of problems of each category that have been randomly chosen. In the second category (Mapping, two columns), we provide the result of our quality analysis of the mapping between WordNet and Adimen-SUMO: the number of problems where both synsets are correctly connected to Adimen-SUMO (Correct column) and the number of problems such that at least one of the synsets is incorrectly connected (Incorrect column). In addition, we also provide the number of mappings where the two synsets are both correctly

| Problem category       | Problems | Mapping                  | Solutions    | Missing solutions |
|------------------------|----------|--------------------------|--------------|-------------------|
|                        |          | Correct | Incorrect | Correct | Incorrect | TT | FT | CM | IM | CK | IK | Knowledge | ATP |
| Multiple Mapping (151) | 1        | 1 (0)   | 0         | 0       | 0         | -  | -  | -  | -  | -  | -  | 1          | 0   |
| Event #1 (24)          | 0        | - (-)   | -         | -       | -         | -  | -  | -  | -  | -  | -  | -          | -   |
| Event #2 (350)         | 1        | 1 (0)   | 0         | 0       | 0         | -  | -  | -  | -  | -  | -  | 1          | 0   |
| Event #3 (2,011)       | 22       | 16 (6)  | 6         | 7       | 7         | 8  | 6  | 14 | 0  | 7  | 1  | 0          | 0   |
| Mapping (2,536)        | 24       | 18 (6)  | 6         | 7       | 7         | 8  | 6  | 14 | 0  | 9  | 1  | 0          | 0   |
| Antonym #1 (71)        | 2        | 2 (2)   | 0         | 2       | 2         | 0  | 1  | 0  | -  | -  | -  | -          | -   |
| Antonym #2 (489)       | 3        | 0 (0)   | 1         | 1       | 1         | 0  | 0  | 1  | 0  | 2  | 0  | 0          | 0   |
| Antonym #3 (2,444)     | 27       | 8 (2)   | 19        | 14      | 5         | 9  | 14 | 0  | 3  | 0  | 0  | 0          | 0   |
| Agent (829)            | 5        | 4 (1)   | 1         | 1       | 0         | 1  | 0  | 1  | 0  | 3  | 0  | 0          | 0   |
| Instrument (348)       | 2        | 2 (2)   | 0         | 0       | 0         | -  | -  | -  | -  | 0  | 2  | 0          | 0   |
| Result (788)           | 12       | 7 (4)   | 5         | 1       | 0         | 1  | 0  | 1  | 0  | 6  | 0  | 0          | 0   |
| Validation (4,969)     | 51       | 25 (11) | 26        | 10      | 0         | 10 | 9  | 19 | 0  | 13 | 2  | 0          | 0   |
| Total (7,505)          | 75       | 43 (17) | 32        | 26      | 7         | 18 | 15 | 33 | 0  | 22 | 3  | 0          | 0   |

Table 6: Detailed analysis of CQs
and precisely connected (Correct column, between brackets). Our criteria for classifying a mapping as only correct or as correct and precise are the following ones: we consider a mapping as correct if the semantics associated to the Adimen-SUMO concept and to the synset are compatible, and a correct mapping is also considered as precise if the synset and the SUMO concept subsume each other. Thus, we consider a mapping as only correct (that is, correct but not precise) when the semantics of the Adimen-SUMO concept is more general than the semantics of the synset. In the third category (Solutions, six columns), we provide the number of solutions classified according to two different criteria:

- In the first two columns (TT and FT columns), we respectively provide the number of proofs for truth-and falsity-tests.

- In the next two columns, we provide the number of solutions for problems where the mapping is correct —both only correct or correct and precise— (CM column) and incorrect (IM column).

- In the last two columns (CK and IK columns), we respectively provide the number of solutions where the knowledge from the ontology that is used is classified as correct (CK column), and the number of solutions that are based on incorrect knowledge of the ontology (IK columns).

Finally, in the last category (Missing solutions, two columns) we sum up the results of our analysis about unsolved problems with a correct mapping —either only correct or correct and precise—: the number of problems that cannot be solved because of lack of knowledge in Adimen-SUMO or due to a misalignment in the knowledge of WordNet and Adimen-SUMO (Knowledge column), and the number of problems that are entailed by the ontology although ATPs do not find a proof within the given resource limits (ATP column).

Next, we sum up the main conclusions extracted from our complete analysis:

- More than two thirds of the problems with an incorrect mapping (20 of 32 problems) belong to the Antonym category problem, especially to the third Antonym subcategory (19 problems). This is mainly due to the poor mapping of WordNet adjectives and satellites. More concretely, many WordNet adjectives and satellites are connected to SUMO processes instead of SUMO attributes.
Among the problems with a correct mapping, the number of problems with a precise mapping is very low (17 of 43 problems). However, this is not surprising because of the large difference between the amount of concepts defined in Adimen-SUMO (3,407 concepts) and WordNet (117,659 synsets).

Our evaluation results (i.e. number of solved problems) are penalized by the poor mapping of WordNet adjectives and satellites, especially in the third Antonym subcategory: 62.50% of problems with a correct mapping are solved (5 of 8 problems) against 47.37% of problems with an incorrect mapping (9 of 19 problems).

The solutions of all the problems that have been solved (33 problems) are based on correct knowledge of the ontology (CK column), for problems with both a correct and incorrect mapping. This means that we have not discovered incorrect knowledge in the ontology by inspecting the proofs provided by ATPs.

Most of the unsolved problems with a correct mapping (22 of 25 problems) are due to the lack of information in the ontology. However, we have also discovered 3 problems for which either the truth- or the falsity-test are entailed by Adimen-SUMO although it cannot be proved by ATPs within the given resources of time and memory.

10. Conclusions and Future Work

A long-standing dream of Artificial Intelligence (AI) has pursued to enrich computer programs with commonsense knowledge enabling machines to reason about our world [22]. This work offers a new practical insight towards the automation of commonsense reasoning with SUMO-based first-order logic (FOL) ontologies. Next, we review the main contributions and results reported in this paper and discuss future work.

First of all, we have introduced a novel black-box testing methodology for FOL ontologies—which is an evolved version of the methodology introduced in [3]—that exploits WordNet and its mapping into SUMO. For this purpose, we have considered different interpretations of the mapping and selected the most productive one for our purposes. By following our proposal, we have obtained more than 7,500 problems (thus, more than 15,000 CQs), as far
as we know the largest set of problems proposed for SUMO-based ontologies. Secondly, we have experimentally evaluated the competency of various translations of SUMO into FOL ontologies —TPTP-SUMO, Adimen-SUMO v.2.2 and Adimen-SUMO v2.6— and the efficiency of several FOL ATPs. In our experimentation, we have checked the coverage of our set of problems by analysing the axioms that are used in the proofs provided by ATPs. Additionally, we have also demonstrated that the proposed set of problems enables to evaluate different features of ATPs since each single system is able to solve different subsets of problems using the same time and memory resources. Finally, we have manually evaluated the quality of a subset of the proposed problems when testing Adimen-SUMO v2.6. From our manual evaluation, we have detected a) some defects in the mapping of synsets (especially in the case of adjectives) and b) some solvable problems for which ATPs find no solution. We plan to propose the inclusion of our proposed set of problems in the CSR domain of the TPTP problem library and its consideration as eligible problems for the LTB division of the CASC competition.

All the resources that have been used and developed during this work are available in a single package, including: a) the ontologies; b) tools for the creation of tests, its experimentation and the analysis of results; and c) the resulting tests for each ontology and the output obtained from different ATPs.

Regarding future work, our plan is to enlarge the proposed set of problems by following different strategies. Among others:

- By considering different interpretations of the WordNet-SUMO mapping.
- By exploiting additional SUMO relations, such as meronymy, hyponymy, etc.
- By exploiting other resources of knowledge such as EuroWordNet Top Ontology ([1]), FrameNet ([34]) or Predicate Matrix ([8]).
- By following white-box testing strategies that focus on the particular representation of the knowledge.

Further, we also aim to exploit unsolved problems in order to improve Adimen-SUMO. For this purpose, we have to analyse whether the classification of

\[\text{http://adimen.si.ehu.es}\]
problems as unsolved is due to the lack of knowledge in Adimen-SUMO. If so, we would consider the possibility of enriching Adimen-SUMO by adding knowledge from WordNet or other resources. Additionally, WordNet itself and its mapping can be evaluated. For example, by detecting synsets that are continuously involved in problems classified as incompatible. Finally, we plan to evaluate the knowledge in the Multilingual Central Repository (MCR) and to check the utility of Adimen-SUMO v2.6 in tasks that involve reasoning about commonsense knowledge, such as Recognizing Textual Entailment (RTE), Natural Language Inference (NLI) or Interpretable Semantic Textual Similarity (ISTS).

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