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Foundational Ontologies meet Ontology Matching: A Survey

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Abstract. Ontology matching is a research area aimed at finding ways to make different ontologies interoperable. Solutions to the problem have been proposed from different disciplines, including databases, natural language processing, and machine learning. The role of foundational ontologies for ontology matching is an important one. It is multifaceted and with room for development. This paper presents an overview of the different tasks involved in ontology matching that consider foundational ontologies. We discuss the strengths and weaknesses of existing proposals and highlight the challenges to be addressed in the future.

Keywords: ontology matching, fondational ontologies, lexicon matching, survey

1. Introduction

A primary purpose of work on ontology is to create a common computable semantics for concepts in the world. An ontology describes the concepts and the relation between these concepts together with constraints on how to interpret them. *Foundational ontologies* aim to create a computable semantics for very general concepts and associated terms. With a large number of ontologies having been created for different domains, as well as different conceptualizations for upper, top or foundational ontologies, the creation of shared semantic descriptions is still an issue.

The role of fondational ontologies in ontology construction, matching and integration is manifold. Their potential for clarity in semantics and a rich formalization are important requirements for ontology development improving ontology quality [41, 52] and preventing bad ontology design [34, 75]. These ontologies may also act as semantic bridges supporting interoperability between ontologies [37, 50, 51].

In the semantic web and linked data in general, as stated in [3], *distinctions such as whether an entity is inherently a class or an individual, or whether it is a physical object or not, are rarely expressed in the linked data, although they have been largely studied and formalised by foundational ontologies*. As stated by the authors, while the first distinction showed its practical importance in modelling and meta-modelling approaches, it is also at the basis of knowledge representation formalisms (such as RDF and OWL) for supporting taxonomic reasoning. The second distinction (physical object or not) is essential to represent the physical world and express their expected physical behaviour (e.g., spatial extension, gravity). Such distinctions are however nearly ubiquitous in ontologies and domain data described by these ontologies.

When a foundational ontology is used in the development and integration of domain ontologies – during or after – *top-down* and *bottom-up* approaches may be considered [76]. With a *top-down approach*, the foundational ontology is used as a reference for deriving domain concepts, taking advantage of the knowledge and experience already encoded in it. In a *bottom-up approach*, one usually matches an existing domain ontology to a foundational one. The latter is more challenging since inconsistencies may exist between domain and foundational ontologies. For example, a domain ontology might be about hypothetical or fictional entities, and a particular foundational ontology might commit only to real entities. Furthermore, one has to deal with different levels of abstraction and also of formalization in the matching process.

Ontology matching is a research area aimed at finding ways to make different ontologies interoperable. The matching process can be seen as the task of generating a set of correspondences (i.e., an alignment) between the entities of different ontologies [18]. Correspondences express relationships between ontology entities. For instance, the concept of *Author* in one source ontology may be marked as equivalent (that can be interpreted as logical equivalence or more informally as a high level of similarity) to the concept of *Writer* in one target ontology, or that *Writer* in the source is subclass of *Person* in the target. One's intuitions about the formalizations of those words may be that they are different, but unless an ontology specifies a formalized definition, they are just labels. A linguistic-based matching algorithm might find them sufficiently similar and evaluators of the match would not have an objective basis for declaring it faulty.

Whereas the area of ontology matching has developed in the last decades, the problem of matching ontologies involving foundational ontologies has seen less development regarding automatic solutions [44, 72]. This is not surprising since matching foundational and domain ontologies is a highly complex task, even when done manually. It requires the deep identification of the semantic context of concepts and, at a minimum, the identification of subsumption relations, and in a way such that the subsumption relations must of course be consistent with the formalization of the subsuming concept in the upper ontology. In fact, subsumption and other relations are often neglected by most state-of-the-art matchers.

There have been many manual efforts to make sense of how different foundational ontologies relate to other lexical and semantic data bases, and how they improve the process of matching domain ontologies. In this paper, we survey various approaches to ontology matching using foundational ontologies to create shared semantics.

An additional challenge is that there is little agreement on many of the possible goals and methods of ontology construction or the formal languages in which to encode an ontology. Developers of ontologies have variously advocated very small upper ontologies or large ones, very expressive formal logics, or very minimal ones as a way to support fast logical inference. Evaluations and surveys have typically been conducted by the authors themselves, or their collaborators and supporters (with the possible exception of [50]).

Considering this scenario, this paper reviews the following tasks of ontology matching involving foundational ontologies:

(i) matching of foundational ontologies;

(ii) matching of foundational ontologies to lexicons;

(iii) matching domain ontologies with the help of foundational ontologies; and

(iv) matching foundational ontologies to domain ontologies.

We discuss the main strengths and weaknesses of existing approaches and highlight the challenges to be addressed in the the future. We consider that this comprehensive study may set the grounds for advancing domain and foundational ontology matching.

The scope of this paper is in using foundational ontologies for matching and integration of ontologies. While this necessarily touches on the topics of how to create or evaluate ontologies themselves, we will address this topic only in the service of evaluation the use case of ontologies for matching. As such, we do not attempt to review all available foundational ontologies, but just study the use of them for matching other ontologies.

The rest of the paper is organised as follows: §2 introduces the different foundational ontologies and ontology matching. §3-§6 discuss the approaches in the categories (i)-(iv) introduced above. §7 discusses the open challenges in the field and §8 concludes the survey.

2. Background

2.1. Foundational ontologies

An ontology typically provides a vocabulary that describes a domain of interest and a specification of the meaning of terms used in the vocabulary. Depending on the precision of this specification, the notion of ontology encompasses several data and conceptual models, for example, sets of terms, classifications, database schemes, or fully axiomatized theories [80].

In particular, ontologies can be classified according to their "level of generality" [31]: *(i) foundational ontologies* describe general concepts (e.g., object, event, quality) and relations (e.g., parthood, participation, dependence, causality), which are independent of a particular domain. These ontologies, also called upper or top-level, are sometimes equipped with detailed logical formalizations, and some include *(ii) domain ontologies* that may also describe the entities related to a particular domain (e.g., biology or aeronautics).[1] A foundational ontology is often characterized as representing commonsense concepts and is focused on concepts that are meta, generic, and domain-independent.

Several foundational ontologies have been developed, influenced by different philosophies and views on how to conceptualize reality. Several comparisons can be found in the literature, as in [42, 50, 76]. Some common criteria for comparing ontologies are artifact representation criteria (dimensions, term and axiom counts, representation languages, modularity) [50], ontological commitments and subject domain and applications [42]. We introduce the main insights behind each proposal. Their different variants and versions, and the availability of alignments to lexical resources (such as WordNet [54]) and ontologies are discussed in the following sections.

A number of well-known ontologies that have documented use in ontology matching and integration efforts are:

- **BFO** [2, 27] [2] (*Basic Formal Ontology*) adopts a *realistic approach* in terms of the existence in time of entities populating the world. It represents the reality into two disjoint categories of *continuant* (independent and dependent continuants, attributes, and locations) and *occurrent* (processes and temporal regions). It has 34 terms and a similar number of axioms. It is defined in OWL[3] and first-order logic language CLIF[4].
- **DOLCE** [23] (*Descriptive Ontology for Linguistic and Cognitive Engineering*) is an ontology of *particulars* which adopts a *descriptive approach*. It is based on a fundamental distinction between *endurant* and *perdurant* entities. *Endurants* represent objects or substances while *perdurants* corresponds to events or processes. The main relation between *endurants* and *perdurants* is that of participation. DOLCE was originally written in the first-order logical language KIF [26] and includes roughly 100 terms and a similar number of axioms. Recent work maintains DOLCE in OWL.
- **Cyc** [32] is a proprietary ontology comprising both an upper-level ontology and a set of domain ontologies in a wide variety of domains. It is meant for the representation of facts, rules, and heuristics to reason about the objects and events of everyday life in the Cyc knowledge base. It involves thousands of "microtheories" with hundreds of thousands of terms and millions of axioms. It comprises OpenCyc is an open source subset of Cyc that is no longer maintained. It is defined in the higher-order CycL language [46].
- **GFO** [38][5] (*General Formal Ontology*) distinguishes processes and objects. Processes unfold in time, they have temporal parts. Objects (called presentials) have no temporal parts, and may only exist on time-boundaries. Concrete individuals exist in time or space whereas abstract individuals do not. While an *endurant* is an individual that exists in time, but cannot be described as having temporal parts or phases; a *process*, on the other hand, is extended in time. It is defined in OWL and has 243 terms.
- **PROTON** [86][6] (*PROTo ONtology*) serves as a lightweight foundational ontology organized in four modules. The *top ontology* module, for instance, distinguishes entity types, such as *object* as existing entities (agents, locations, vehicles); *happening* as events and situations; and *abstract* as abstractions that are neither objects, nor happenings. It contains about 500 classes and 150 properties (650 terms), providing coverage of the general concepts necessary for a wide range of tasks, including semantic annotation, indexing, and retrieval. This ontology is codified in OWL-Lite.
- **SUMO** [57, 64][7] (*Suggested Upper Merged Ontology*) is defined in the higher order logical language of SUO-KIF[8]. It includes dozens of domains

[1] We here follow the terminology proposed by [31] in distinguishing top-level and domain ontologies regarding their level of generality. More recently, the term *Core Ontology* [15, 68] has been used to refer to ontologies whose generality level lays half-way between top-level and domain ontologies. These can be seen as abstractions over several domain ontologies capturing concepts that crosscut several domain conceptualizations. For the purpose of this article, core ontologies are seen on par with domain ontologies. For example, the SWEET ontology or the OM (Observations and Measurements) ontology, both of which are discussed in section 6 are examples of core ontologies.

[2] https://github.com/bfo-ontology/BFO/wiki

[3] https://www.w3.org/OWL/

[4] https://www.iso.org/standard/39175.html

[5] http://www.onto-med.de/ontologies/gfo/

[6] http://ontotext.com/proton

[7] http://www.ontologyportal.org

[8] https://github.com/ontologyportal/sigmakee/blob/master/suo-kif.pdf

Ontology	*#Entities*	*Formats*	*URL*
BFO	34 terms	OWL,CLIF	https://github.com/bfo-ontology/BFO/wiki
DOLCE	100 terms/axioms (depends on the version)	OWL,KIF	http://www.loa.istc.cnr.it/ontologies/DOLCE-Lite.owl
Cyc	100k terms and 1M axioms	CycL	http://www.cyc.com
GFO	243 terms	OWL	http://www.onto-med.de/ontologies/gfo/
PROTON	650 terms	OWL-Lite	http://ontotext.com/proton
SUMO	20.000 terms, 80.000 axioms	SUO-KIF	http://www.ontologyportal.org
UFO	51 terms, 595 axioms (depends on the version)	FOL, SROIQ (OWL)	https://nemo-ufes.github.io/gufo/

Table 1

Summary of foundational ontologies used in ontology integration, discussed in the next sections

ontologies, and contains roughly 20,000 terms and 80,000 logical statements (axioms). It has an associated toolset [62], translations to languages used in theorem proving [6, 63] and a complete set of alignments to WordNet [58]

– **UFO** [33, 35][9] (*Unified Foundational Ontology*) has been developed with the intention of providing foundations for Conceptual Modeling. It started as an unification of the GFO and the foundational ontology of universals underlying OntoClean[10] [30]. UFO is divided in three parts representing different aspects of reality: A - endurants (dependent and independent objects and their types), B - perdurants (events and situations), and C - social entities, with notions such as beliefs, desires, intentions, etc. UFO-A has been formalized in First-Order Modal Logics [33, 35, 36] (e.g., the microtheory of endurant universals contains 22 terms and 31 axioms [36]; the microtheory theory dealing with relations contains 25 terms and 20 axioms) [19]; UFO-B has been completely formalized in First-Order Logics (26 terms and 185 axioms) with a (partial) translation to $\mathcal{SROIQ}$ [4]. Taken together, the microtheory of endurants universals, the one of relations, and UFO-B amount to circa 67 terms and 236 axioms. UFO has also a partial translation to OWL termed gUFO (gentle UFO) [1], which is composed of 51 terms (class declarations) and 595 axioms.

This list summarized in Table 1 gives an idea of the variety of foundational ontologies. One can see the variety in number of entities ranging from dozens to thousands, on the other hand there is some uniformity in adoption of the OWL standard in a majority of the listed ontologies. We point out as well that most ontologies do not publish versioned releases and exact number of classes or identifiers are not available for most. We tried to provided the most up to date counts of terms or at least order of magnitude counts for the larger ones, along with the best reference available to any online repositories where the latest versions are available.

The list is also not exhaustive as we describe only the ontologies that are more often cited in the the task of ontology matching. There are other top or foundational ontologies such as SOWA's ontology[11], YAMATO [55], GIST [88][12], KYOTO[13], PSL (Process Specification Language (PSL) [28] and BORO (Business Objects Reference Ontology) [16].

2.2. Ontology matching

Ontology matching refers to a process that consists of generating an alignment (A') from a set of ontologies Ω, usually a pair of ontologies ($\Omega = \{o_1, o_2\}$).

Definition 1 (Matching process)**.** *The matching process can be seen as a function f which, from a pair of ontologies o_1 and o_2 to match, an input alignment A, a set of parameters p, and a set resources r, returns an alignment A' between o_1 and o_2:*

$$A' = f(o_1, o_2, A, p, r)$$

Each of the elements featured in this definition can have specific characteristics which influence the difficulty of the alignment task.

An alignment (A or A') consists of a set of correspondences $\{c_1, c_2, ..., c_x\}$:

Definition 2 (Alignment)**.** *An alignment $A_{o_1 \to o_2}$ is a set of correspondences*

[9] http://dev.nemo.inf.ufes.br/seon/UFO.html

[10] http://www.ontoclean.org

[11] http://www.jfsowa.com/ontology/toplevel.htm

[12] https://www.semanticarts.com/gist/

[13] http://kyoto-project.eu/xmlgroup.iit.cnr.it/kyoto/index.html

$\{c_1, c_2, ..., c_n\}$. *$A_{o_1 \rightarrow o_2}$ is directional between a source ontology o_1 and a target ontology o_2.*

A correspondence expresses a relation r between ontology entities of o_1 and o_2. Here, the ontology entities are *members* of the correspondence:

Definition 3 (Correspondence)**.** *A correspondence c_i is a tuple (e_1, e_2, r). e_1 and e_2 are the members of the correspondence. They can be simple or complex expressions with entities from respectively o_1 and o_2:*

– *if the correspondence is* ***simple****, both e_1 and e_2 are simple expressions.*
– *if the correspondence is* ***complex****, at least one of e_1 or e_2 is a complex expression, involving union, intersection, disjunction, cardinality restrictions, etc.*
– *r is a relation, e.g., equivalence ($\equiv$), more general ($\sqsupseteq$), more specific ($\sqsubseteq$), disjointedness ($\perp$) holding between e_1 and e_2.*

The correspondence $\langle e_1, e_2, r\rangle$ asserts that the relation r holds between the ontology entities e_1 and e_2. One have to distinguish between more and less rigorous interpretations of relations. The equivalence relation, for example, can be interpreted as logical equivalence or more informally as a high level of similarity. Back to the example in the introduction, consider the fragment of the ontologies *ekaw*[14] and *cmt*[15] in Figures 1 and 2, respectively. The format used to represent the ontologies is described in [83]. The following correspondences can been established between these two ontologies: (*ekaw:Paper,cmt:Paper,*$\equiv$) is a simple correspondence; (ii) (*ekaw:AcceptedPaper, $\exists$cmt:hasDecision.cmt:Acceptance,*$\equiv$) is a complex correspondence with constructors.

While the RDF alignment format provided in the Alignment API[16] [14] is the format *de facto* used in the Ontology Alignment Evaluation Initiative (OAEI) campaigns for representing simple alignments, correspondences can also be represented as OWL 2 subclass, equivalence, and disjointedness axioms (with confidence values represented as axiom annotations). Alternatively, the EDOAL[17] language (Expressive and Declarative Ontology Alignment Language) extends the alignment format in order to represent complex correspondences.

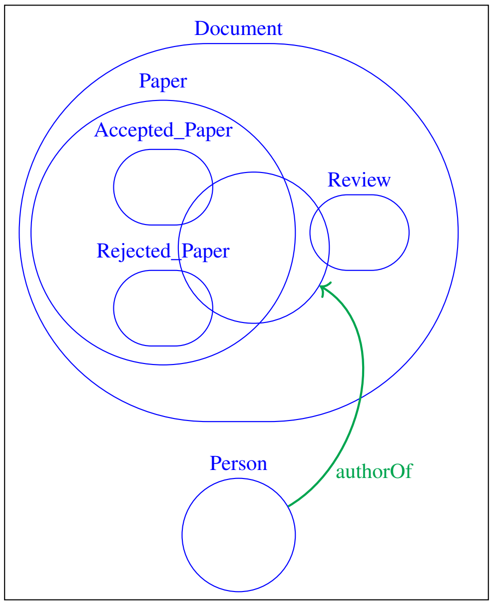

Fig. 1. Fragment of *ekaw* ontology.

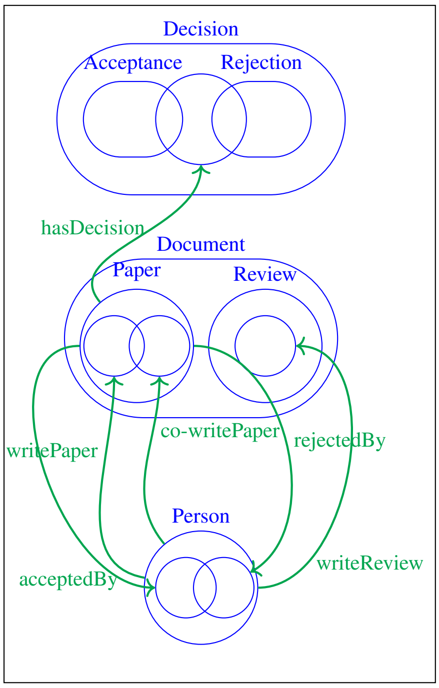

Fig. 2. Fragment of *cmt* ontology.

In the following, we discuss the use of foundational ontologies in different matching tasks: (i) matching of foundational ontologies; (ii) matching of foundational

[14] http://oaei.ontologymatching.org/2019/conference/data/ekaw.owl
[15] http://oaei.ontologymatching.org/2019/conference/data/cmt.owl
[16] http://alignapi.gforge.inria.fr/format.html
[17] http://alignapi.gforge.inria.fr/edoal.html

ontologies to lexicons; (iii) matching domain ontologies with the help of foundational ontologies; and (iv) matching foundational ontologies to domain ontologies.

3. Matching foundational ontologies

As stated in [43], while the purpose of a foundational ontology is to address interoperability among ontologies, the development of different foundational ontologies re-introduces the interoperability problem. As briefly discussed in the previous section, these ontologies have been developed directed at different classes of applications, as well as relying on different theoretical assumptions.

Early work addressed this problem [27, 79, 85] from different perspectives on the alignments. While [27] compared specific treatments of fundamental issues (as significant discrepancies related to universals and particulars, qualities, constitution and spatio-temporality) and how similar notions apply differently in BFO and DOLCE, [79] compared the primitive relations (dependence, quality, and constitution) between these ontologies. In [85], the alignment between BFO and DOLCE was established in order to conciliate their respective realistic and cognitive points of view and to integrate medical data. While 100% of BFO categories were aligned to DOLCE, 81% of DOLCE categories were aligned to BFO.

More recently, [89] compares BORO and UFO ontologies according to the their metaphysical choices that define their structure and composition. Instead of comparing terms in both ontologies, the authors compare how the two approaches address issues such as *identity* and *dynamic classification*, the treatment of *relationships* (i.e., instances of *relational properties*), as well as the relation between *existence* and *time* in the two approaches. The radical difference between these two ontologies, hence, reflect deeper differences in ways of conceiving reality.

Other studies addressed other foundational ontologies. In [43], alignments between BFO, DOLCE and GFO have been established with automatic matching tools and manually, with substantially fewer alignments found by the matching tools. The alignments in the context of the whole ontology revealed a considerable amount of logical inconsistencies. This work has been extended in [74] in two ways: considering matching systems participating in OAEI 2018, and a new pair of aligned foundational ontologies (SUMO and DOLCE). The alignments in [43] and [59] served as a reference alignment to automatically evaluate the matchers. Examples of reference correspondences include: (*bfo:Occurrent,dolce-lite:perdurant,*$\equiv$) and (*dolce-lite:artifact,sumo:Device,*$\sqsupseteq$).

Overall, the results found are in line with what has been reported when evaluating the behaviour of matchers in the task of matching domain and foundational ontologies, which would also require identification of subsumption relations [70]. Current tools fail on correctly capturing the semantics behind the ontological concepts, which requires deeper contextualization of the concepts on the basis of their hierarchy and axioms. Addressing the identification of subsumption relations, the approach in [40] relies on extracting hypernym relations from ontology annotations for establishing such kind of correspondences. Results on exploiting lexico-syntactic patterns and definitions layout on DOLCE and SUMO were evaluated on a manually generated subsumption reference.

From another perspective, the core characterization of mereotopology (a theory of physical parts) of SUMO and DOLCE has been studied in [56], relating their axiomatizations via ontology alignments. This included corrections and additions of axioms to the analyzed theories which eliminate unintended models and characterize missing ones. Finding alignments between DOLCE and SUMO was also addressed in [59], where the SmartDOLCE and SmartSUMO ontologies have been developed on the basis of DOLCE and SUMO. The alignment of the just the taxonomic statements from SUMO to DOLCE involved extracting the upper-level of SUMO and the non-trivial task of aligning the remaining concepts to appropriate DOLCE categories.

Aligning foundational ontologies reveals also the problem of matching their different versions. In [77], a method for tracking, explaining and measuring changes between successive versions of BFO1.0, BFO1.1, and BFO2.0 was applied. The aim was to provide a more comprehensive analysis of the changes with respect to the BFOConvert tool[18] which provides an alignment between previous BFO versions, as this resource is limited to allow for a full understanding of the impact of the changes.

Formalizeations [10] within the Common Logic Ontology Repository (COLORE), were used in the specification of alignments between upper ontologies in

[18]http://ontobull.hegroup.org/bfoconvert (viewed on 25/03/2019)

Matching foundational ontologies			
Work	*Ontologies*	*Approach*	*Available alignment*
[27]	BFO 1.0, DOLCE	Manual comparison	-
[79]	BFO 1.0, DOLCE	Manual comparison	-
[85]	BFO 1.0, DOLCE	Manual alignment	Set of triples
[43]	BFO 1.1, DOLCE-Lite, GFO	Manual, matching tools	List at Romulus*
[77]	BFO 1.0, BFO 1.1,BFO 2.0	Semi-automatic (change-tracking)	-
[59]	SUMO, DOLCE	Manual alignment	-
[56]	SUMO, DOLCE-CORE	Manual alignment	FOL alignments
[74]	BFO, GFO, DOLCE-Lite, SUMO	Matching tools	Alignment API format
[40]	DOLCE-Lite, SUMO	Hypernym relation extraction	Alignment API format

Table 2

Summary of matchings of foundational ontologies (*http://www.thezfiles.co.za/ROMULUS/ontologyAlignment.html)

[29]. These alignments serve for the verification of foundational ontologies. Similarly, [11] shows how to apply techniques for ontology verification to link interpretations among ontologies.

Table 2 summarizes work on matching of foundational ontologies. They are mostly manual efforts, with a few of the resulting alignments made available.

4. Matching foundational ontologies to lexicons

Several efforts in equipping lexical resources with foundational ontologies have been made in order to associate a formal semantics to their lexical layer. As stated in [22, 23], while WordNet has been used in numerous work as an ontology, where the hyponym relations between word senses are interpreted as subsumptions relation between concepts, it is only serviceable as an ontology if some of its links are interpreted according to a formal semantics that tell us something about the world and not just about language.

For example, WordNet has the sense of "chair" as a hyponym of "seat" but only an English gloss meant for humans to read for each, and no logical semantics that defines the hyponym link, with the result that hyponyms are often incorrectly treated by users as being logically transitive. An ontology would, at a minimum, define the axiom of transitivity, and state that it holds on the hyponym relation. Most ontologies have little more than class/subclass relations however. One might also want to state that a chair is a artifact made by humans with the intent for use in supporting a seated humans. Some upper ontologies have axioms that define their terms, and some large taxonomies have terms for specific things like chairs, but very few have axiomatized large number of detailed objects, processes and relationships. This poses a problem for matching algorithms if there aren't both detailed formalizations that can be used to objectively determine a correct match and a large inventory so that matches are not to trivially general terms like object or event.

A number of researchers have investigated different ontological problems in treating WordNet as an ontology (e.g., confusion between concepts and individuals, constraints violations, heterogeneous levels of generality, etc.) [22] and provided the WordNet taxonomy with more rigorous semantics. First the WordNet taxonomy was reorganized to meet the OntoClean [30] methodology requirements, and the resulting upper level nouns were then mapped to DOLCE classes representing their highest level categories. This alignment is concentrated on the noun database, since most particulars in DOLCE describe categories whose members are denoted by nouns. The result is the OntoWordNet resource expressing alignments between WordNet 1.6 version and DOLCE Lite Plus. An extension is presented in [24] in order to extract association relations from WordNet, and to interpret those associations in terms of a set of conceptual relations in DOLCE.

Later, this alignment has been updated [25] with a revision of the manual alignments and different versions of DOLCE and WordNet, WordNet 3.0 and (DOLCE UltraLitePlus), which is a simplified version of DOLCE Lite Plus, intended to make classes and properties names more intuitive and express axiomatizations in a simpler way, among other features.

While these works focused mostly on WordNet noun synsets, [82] extended the previous alignments by aligning verbs according to their links to nouns denoting perdurants, transferring to the verb the DOLCE class assigned to the noun that best represents that verb's occurrence. They argue that many NLP applications need to deal with events, actions, states, and other temporal entities that are usually represented by verbs.

Matching foundational ontologies to lexicons			
Work	*Ontologies*	*Approach*	*Available alignment*
[24?]	DOLCE-LitePlus,DOLCE-UltraLite/WordNet1.6	Semi-automatic (NLP, disamb., A-links)	OWL version*
[25]	DOLCEPlusDnS Ultra Lite/WordNet3.0	Semi-automatically (transitive closure)	RDF dataset
[82]	DOLCE-LitePlus/WordNet3.0 (verbs)	Semi-automatic (annotation tool, links)	-
[78]	BFO2.0/WordNet3.0	Semi-automatic (matching rules)	-
[67]	Cyc/WordNet1.6	Semi-automatic (interactive tool, rules)	-
[58]	SUMO/WordNet1.6/3.0	Manual	Textual format
[17]	SUMO, YAGO, WordNet, Wikipedia	Semi-automatic	SUMO axioms
[45]	UF0/WordNet3.0	Automatic (SemanticMapper)	-

Table 3

Summary of matching with lexicons (*http://www.ontologydesignpatterns.org/ont/wn/)

The alignment of WordNet to other foundational ontologies has been also addressed. In [78], a semi-automatic method for aligning WordNet 3.0 and BFO2.0 is described. It adopts previous alignments between WordNet and the KYOTO ontology, whose top layer is based on DOLCE. The method involves manually creating a set of alignments between the ontologies and implementing a set of matching rules.

In [67], the authors report the matching and integration of several background resources and ontologies of varying complexity to the Cyc knowledge base. These resources and ontologies included large pharmaceutical and medical thesauri and large portions of WordNet. For this task, ontologists have been trained with domain experts and interactive clarification dialog-based tools were developed to enable experts to directly match/integrate their ontologies. In [58], SUMO was originally mapped manually to WordNet 1.6 and then manually updated to 3.0 [19]. It is the only manual alignment of an ontology to every word sense in WordNet.

SUMO and WordNet were used in a semi-automated process to match the millions of terms in the YAGO[20] taxonomy and create a single large ontology and Factbase [17].

Finally, in [45], WordNet has been extended by applying the notion of *semantic types* in order to establish matching rules between the noun synsets of WordNet and the top-level constructs of the UFO ontology. The proposed rules were validated through an experiment with approximately 5,200 sample correspondences and average accuracy of 93%.

[19]https://github.com/ontologyportal/sumo/tree/master/WordNetMappings

[20]http://yago.r2.enst.fr

Table 3 summarizes the works presented in this section. There are some available alignments, approaches are mostly semi-automatic, with one case of manual alignment and one case of automatic alignment. WordNet is the lexical resource that is considered in all work listed and two different versions are involved in the alignments (1.6 and 3.0).

5. Matching domain via foundational ontologies

Foundational ontologies provide a reference for rigorous comparisons of different ontological approaches, and a framework for analysing, harmonizing, matching and integrating existing domain ontologies [59]. In domain ontology matching, in particular, they act as semantic bridges to help the task. For instance, reducing the matching space to the entities under a same category e.g., avoiding matching *dolce:endurants* to *dolce:perdurants*.

Despite the potential gain of exploiting foundational ontologies in domain ontology matching, few works have addressed this alternative, possibility due to the still lack of systematic alignments between domain and foundational ontologies. This gain has been quantitatively measured in [51], where a set of algorithms exploiting such semantic bridges are applied. The circumstances of cases where foundational ontologies improve domain ontology matching, with respect to approaches ignoring them, were then studied. The experiments were conducted with SUMO-OWL (a restricted version of SUMO), OpenCyc and DOLCE and demonstrate that overall the alignment via upper ontologies impacts in F-measure positively. Additionally, in [60] a set of alignment patterns based on OntoUML (a conceptual modeling language based on UFO) are applied to a set of alignments generated by matching

Matching domain ontologies via foundational ontologies			
Work	*Ontologies*	*Approach*	*Available alignment*
[48]	SUMO, Cyc/SENSUS	Semi-automatic (LOM matcher)	-
[51]	SUMO-OWL, OpenCyc, DOLCE/ 17 ont. (agent, bibtex, etc).	Automatic (structural matching)	-
[81]	BFO/GO, INOH Event	Automatic (FOAM+OBOAEA)	-
[60]	UFO/Conference	Manual pattern analysis	-

Table 4

Summary of matching via foundational ontologias

systems. An analysis of the impact of patterns to avoid common errors was presented.

The semi-automatic LOM matcher [48] combines WordNet synset matching (checking terms from the ontologies to be matched sharing common synsets) and *type matching*. This strategy employs SUMO to determine the ontological category of each word constituent for matching using the alignments from WordNet synsets to SUMO. LOM takes the source terms and collects the set of SUMO terms that their synsets map to, and then compares the SUMO term sets to their counterpart for each term in the target ontology.

From a manually established alignment between biomedical ontologies and BFO, in [81], a matching approach relies on filtering out correspondences at domain level that relate two different kinds of ontology entities. The matching approach is based on a set of similarity measures and the use of foundational ontology as a parameter for better understanding the conceptual nature of terms within the similarity calculation step. Besides the reported improvement in the results obtained, the introduction of foundational ontologies in the alignment process increased the influence of semantic factors in this task, further expanding the universe of information to be explored during the alignment.

Table 4 summarizes the use of foundational ontologies as an aid to the of matching domain ontologies. Here the automatic approaches are adopted more frequently. Alignments, however, were not found available.

6. Matching domain to foundational ontologies

Methodologies for constructing ontologies should not neglect the use of foundational ontologies and may better address it in a *top-down* approach [2, 41]. As one example, existing methodologies including OntoUML [20], allow for creating a domain or core ontology compliant to UFO.

While matching foundational ontologies is mostly manually done, with more automation in matching domain ontologies via foundational ones, in this section, both approaches have been performed.

6.1. Manual Alignment

Many approaches for mapping rely on a manual alignment process. In [8], DOLCE was used to integrate two geoscience knowledge representations, the GeoSciML schema and the SWEET ontology, in order to facilitate cross-domain data integration. The aim was to produce a unified ontology in which the GeoSciML and SWEET representations are aligned to DOLCE and to each other. In that perspective, DOLCE works as a semantic bridge and this approach fits in the category of domain matching with foundational ontologies. The alignments have been manually established and representation incompatibility issues have been discussed so far. Similarly, in [66], manual alignments were established between the O&M (Observations and Measurements) ontology and DOLCE, in order to restrict the interpretations of entities in the O&M model and to make explicit the relations between their categories.

DOLCE has been manually aligned to the domain ontology describing services (OWL-S) in [52], in order to address its conceptual ambiguity, poor axiomatization, loose design and narrow scope. They have also developed a core ontology of services to serve as middle level between the foundational and OWL-S, and can be reused to align other Web Service description languages.

In [12], several schemata of FactForge, which enables SPARQL queries over a LOD cloud, have been aligned to the foundational ontology PROTON in order to provide a unified way to access to the data. The alignments were created by knowledge engineers through a manual process. Equivalence e.g., (*geonames:Country,proton:Country,*≡) and subsumption relations (*Proton:Situation,*

Matching domain ontologies to foundational ontologies			
Work	*Ontologies*	*Approach*	*Available alignment*
[52]	DOLCE/OWL-S	Manual	-
[8]	DOLCE-LitePlus/GeoSciML2.0, SWEET1.1	Manual	UML-syntax
[49]	DOLCE Ultralite/Mobile services ontology	Automatic (lexical+reasoning)	-
[71]	DOLCE-LitePlus/OAEI Conference	Automatic (indirect matching)	-
[72]	DOLCE-LitePlus, DOLCE Ultralite, SUM0/Conf, SSN, CORA	Automatic (indirect+embeddings)	Alignment API format [14]
[3]	DOLCE-LitePlus/DBPedia	Automatic (machine learning)	-
[12]	PROTON/DBPedia, Freebase, Geonames	Manual	-
[39]	PROTON/DBPedia, Freebase, Geonames	Automatic (BLOOMS+)	-
[13]	PROTON,OpenCyc(UMBEL)/Freebase, Geonames		-
[81]	BFO/GO, INOH Event	Manual	-
[73]	SUMO/OAEI Conference	Manual (via WordNet)	-
[65]	SUMO/CORA Robotics	Manual	http://purl.org/ieee1872-owl

Table 5

Summary of matching with domain ontologies and cross-domain ontologies (*https://github.com/danielasch/top-match).

DBpedia:OlympicResult, $\sqsupseteq$) between DBPedia, Geonames and Freebase concepts and PROTON classes have been established. In other similar work, [13] includes an open-source extract of the OpenCyc knowledge base (UMBEL).

As stated in §5, manual alignments have also been established between biomedical ontologies and BFO, in [81]. In this line, [9] analysed the "compatibility" between an ontology of the biomedical domain (UMLS) and the Cyc Ontology, by manually aligning UMLS to Cyc.

In [73], ontologies from the OAEI Conference track have been manually aligned to SUMO. As a complete manual alignment between SUMO and WordNet is available, such alignments have been used as bridges to facilitate the matching task. Four annotators have been worked on the alignments. Table 6 shows a fragment of the spreadsheet used for the annotators to align the domain concepts to the SUMO concepts.

During the process of alignment, several difficulties arose for interpreting the real meaning that the concept represents in the domain ontology. For instance, the concepts `cmt:Bid` and `cmt:Preference` had no description clarifying theiruse, and no sub- or super-concepts that could be used to clarify their meaning. In addition, some concepts represented in the ontology present other kind of problems such as doubts regarding ontology elements' adequacy, for example, the concept `edas:ReviewRating`, for which, according to the discussion raised by the evaluators, a rating could be a relationship between a thing, an agent and a rating value, rather than a class or individual as it would appear.

In contrast, one can examine a SUMO definition of a term such as `sumo:FormalMeeting` and see that it is necessarily a `sumo:Meeting` which is not a `sumo:SocialParty`, that it must be temporally preceded by a `sumo:Planning` which has the `result` of creating the meeting, as well as constraints that other events like a `sumo:Resolution`, which to be considered as such, may only occur at a `sumo:FormalMeeting`. It provides information something like the level of detail in a modern dictionary, but with the definitions expressed in logic, rather than human language, so that a machine can perform computation (and consistency checking) with those definitions. The cases described above consist of ontological representation problems commonly present in lightweight ontologies, and hinder the reuse and reliability of the represented knowledge. In addition, they highlight the importance of advancing in research that uses foundational ontologies to give more formalization to domain ontologies.

In [61], existing alignments between DBPedia ontology and DOLCE-Zero[21] [21, 23], a subset of the modules of the formal ontology, are used to identify inconsistent statements (systematic errors or antipatterns) in DBPedia. DOLCE-Zero simplifies some of the distinctions in DUL, which has been created to optimize the alignment of WordNet used by the Tipalo method for automatic typing of Wikipedia resources [25]. Systematic errors are sets of individual errors following a similar pattern and having a common root cause (e.g., a wrong correspondence). The

[21]http://www.ontologydesignpatterns.org/ont/dul/d0.owl

Domain concept	WordNet synsets(S)	SUMO concept
cmt#Conference	S1: conference group discussion	1: Communication+
	S2: league conference	2: SportsLeague+
	S3: conference	3: **FormalMeeting**
cmt#Decision	S1: decision determination conclusion	1: **Learning+**
	S2: decision determination conclusion	2: Deciding+
	S3: decisiveness decision	3: TraitAttribute+
	S4: decision	4: ConstantQuantity+
	S5: decision	5: ConstantQuantity+

Table 6

Fragment of the spreadsheet for the manual alignment between *cmt* ontology in Figure 2 and SUMO, via WordNet.

alignment has been defined by a DOLCE-Zero designer. By using these alignments and by combining reasoning and clustering of the reasoning results, errors affecting statements can be identified at a minimal human workload.

6.2. Automatic and Semi-Automatic Alignment

While the previous proposals mainly generate manual alignments, BLOOMS+ [39] is an early work on automatising the process. It has been used to automatically align PROTON to LOD datasets using as gold standard the alignments provided in [12]. BLOOMS+ first uses Wikipedia to construct a set of category hierarchy trees for each class in the source and target ontologies. It then determines which classes to align using 1) similarity between classes based on their category hierarchy trees; and 2) contextual similarity between these classes to support (or reject) an alignment. BLOOMS+ significantly outperformed existing matchers in the task.

In [71] the authors have proposed an automatic approach for matching domain and foundational ontologies that exploits existing alignments between WordNet and foundational ontologies. The matching process is divided in two main steps. The first step identifies the correct synset to a concept and the second one identifies the correspondence of a domain concept to a foundational concept. The approach has been evaluated using DOLCE and domain ontologies from the OAEI conference data set[22], with the help of the alignments provided in [24, 58]. This work has been further extended in [72], where two similarity measures for synset disambiguation have been adopted: (1) an adaptation of the Lesk[47] measure and (2) word embeddings[53] similarity. The evaluation has been also extended including DOLCE and SUMO ontologies and their alignments to WordNet and three domain ontologies (SSN[23], CORA[24], and OAEI Conference). SSN (W3C Semantic Sensor Network Ontology) describes sensors, devices, observations, measurements and other terms, enabling reasoning of individual sensors and the connection of them. A recent version of SSN includes a lightweight core ontology called SOSA (Sensor, Observation, Sample, and Actuators). SSN is aligned to SOSA and both ontologies are aligned to DOLCE Ultralite (DUL). SSN is composed of 18 first level concepts, from those, 8 concepts are aligned to the top ontology DUL. CORA (IEEE Core Ontology for Robotic and Automation) [65] is an effort of the IEEE Ontologies for Robotics and Automation Working group (ORA). It specifies the main concepts, relations, and axioms of robotics and automation domains. CORA is aligned to the SUMO top-level ontology. CORA is composed of 34 first level concepts, from which 29 of them are aligned to SUMO.

In [49] WordNet was used as background knowledge, and their matching approach combines concept definition enrichment, disambiguation and filtering of candidate correspondences with inconsistency detection. The approach has been used for matching DOLCE+DnS Ultralite and a domain ontolology describing mobile services.

Automatic foundational distinctions of LOD entities (class vs. instance or physical vs. non-physical objects) is done in [3] with two strategies: an (unsupervised) alignment approach and a (supervised) machine learning approach. The alignment approach, in particular, relies on the linking structure of alignments between DBpedia, DOLCE, and lexical linked data, using re-

[22]http://oaei.ontologymatching.org/2017/conference/index.html

[23]https://www.w3.org/TR/vocab-ssn/

[24]IEEE Standard Ontologies for Robotics and Automation," in IEEE Std 1872-2015 , vol., no., pp.1-60, 10 April 2015

sources such as BabelNet, YAGO and OntoWordNet. For instance, they use the paths of alignments and taxonomic relations in these resources and automated inferences to classify whether a DBpedia entity is a physical object or not.

Table 5 summarizes work in alignments between domain and foundational ontologies. Several efforts have been made to align DOLCE to domain ontologies, SUMO and PROTON are also considered in more than one work. These projects use different domain ontologies, and results are unavailable is most of the cases, therefore a detailed third-party comparison of approaches is yet not possible.

7. Discussion

The following sections discuss a series of issues regarding matching of foundational ontologies: the complexity of the task, the automation of systems with capabilities to include such alignments, the lack of evaluation data sets, the evolution of different versions and the problems that poses, the desired variety and lack of expressiveness in the alignments, and finally, multilingualism.

7.1. *Complexity of the task*

As seen in the previous sections, most approaches still rely on manually or semi-automatically established alignments. This task is far from being trivial, even when done manually. This has been recently corroborated in [84], where manually classifying domain entities under foundational ontology classes is reported to be very difficult to do correctly. Manual ontology matching is also an expensive task that may introduce a bias as it represents a point of view expressing the interpretation of the concepts influenced by the background of the expert. As knowledge on foundational ontologies is specialized, it is important that such evaluation considers an overview of different experts in this area. Moreover, while manual alignment on a small set of concepts is feasible, bigger data sets would require considerable effort. The findings in [84] also point out the need for improving the methodological process of manual integration of domain and foundational ontologies, in accordance with what has been stated in [41].

7.2. *Automation*

While more automation is an obvious requirement in the field, the poor performance of solutions addressing automatically matching different foundational ontologies or with domain ontologies have demonstrated the difficulty of the task, as reported in experiments evaluating current matching tools [43, 69]. Current tools fail on correctly capturing the semantics behind concepts (even when such semantics are present), which requires deeper contextualization on the basis of hierarchies and axioms. In that sense, further context and documentation is required, in particular for domain ontologies, to help identifying the right semantics (e.g, the ontologies from the largely used OAEI Conference dataset have a very poor lexical layer and limited or non-existent axiomatized semantics).

Furthermore, while diverse (domain) ontology matching approaches rely on external background knowledge, (BabelNet[25], WordNet[26], UMLS[27], etc.), the coverage of foundational ontologies in these resources is still low. More recently, the resource Framester[28], exposed as a knowledge graph, addresses this aspect as a hub between several resources such as VerbNet[29], BabelNet, DBpedia[30], and YAGO[31]. Hence, matchers need to be improved to include more abstract and philosophical semantic relations and semiotic matching, to take advantage of structural features of the ontologies and axioms in order to better compare their formal definitions, and also of background knowledge from external resources, targeting subsumption and other relations. These have to be combined with logical reasoning techniques for guarantee the consistency of the generated alignments. The current approaches have to be thus revised to better deal with the specificities of matching with foundational ontologies. While automatic approaches have been mostly manually evaluated, with few exceptions [12, 72], systematically evaluations of matching systems have been so far dedicated to domain ontologies.

[25] https://babelnet.org
[26] https://wordnet.princeton.edu
[27] https://uts.nlm.nih.gov/home.html
[28] https://lipn.univ-paris13.fr/framester/
[29] https://verbs.colorado.edu/verbnet/
[30] https://wiki.dbpedia.org
[31] http://yago.r2.enst.fr

7.3. *Other relations than equivalence*

Besides the points raised above, the task requires the identification of other relations than equivalences, such as subsumption and meronymy. The latter is largely neglected by current matchers. In particular, the main problem of matching foundational and domain ontologies is that, most matchers typically rely on string-based techniques as an initial estimate of the likelihood that two elements refer to the same real world phenomenon, hence the found correspondences represent equivalences with concepts that are equally or similarly written. However, in many cases, this correspondence is not the case [69]. In fact, when having different levels of abstraction it might be that the matching process is capable of identifying subsumption correspondences rather than equivalence, since the foundational ontologies have concepts at a higher level.

7.4. *Evaluation*

Despite the variety of tasks in the OAEI campaigns[32], evaluations involving foundational ontologies have not been addressed. Producing comprehensive evaluation data sets on which matching solutions can be evaluated would foster the development of approaches involving foundational ontologies and support a next generation of semantic matching approaches. With that respect, few of the established alignments generated by the approaches have being publicly made available. Furthermore, very few of them adopted a format that can be processed by automatic tools. Only [71] adopts the Alignment API Format, the standard *de facto* adopted in the OAEI campaigns.

7.5. *Versioning*

Another aspect refers to the evolution or the consistency of alignments with respect to the evolution or the different variants of the ontologies. For example, DOLCE and its different variants have been used in diverse proposals, as many efforts have been dedicated to the development of this ontology. DOLCE has been exposed with reduced axiomatization and extensions with generic or domain plugins, such as for DOLCE-Lite [24], DOLCE Lite Plus[33] or still DOLCE+DnS Ultralite[34]. Besides their substantial differences in the hierarchical organization and expressiveness, these versions are mostly compatible, what is not the case for other ontologies. For instance, BFO 2.0 represents major updates to BFO not strictly backwards compatible with BFO 1.1 and a manual alignment was required to express their incompatibilities. UFO is also currently being extended by incorporating a new theory of types (including higher-order types), as well as a fuller theory of relationships and events [35]. Despite being, to a large extent, backwards compatible with the original ontology, these are important changes of UFO 2.0.

Another issue is related to the evolution of the resources aligned to the ontologies. As stated in [61], conflicts may arise between an alignment defined on a version, and a newer version. The alignment provided for an older version may become incoherent in case of a non-conservative change of the ontology in the newer version. It is the case in the alignments between DOLCE and the different versions of DBPedia. Taking the example presented by the authors, for instance, *dbo:team* used to hold between career stations (professional situations of e.g. an athlete) and teams in DBpedia 3.9 ontology, but in DBpedia 2014 it holds between agents and sports teams. Since *dul:Situation* (aligning *dbo:CareerStation*), and *dul:Person* (aligning *dbo:Athlete* are disjoint, inconsistencies are detected. In particular, in particular where a) the DBpedia2014 ontology has used DBpedia 3.9 alignments, but the basic ontology had changed; and b) some properties are applied ambiguously, which should lead either to a change of the alignment, or of the DBpedia data or ontology.

Evolving alignments to cope with the different versions of the ontologies is still an open challenge.

7.6. *Expressiveness*

Most alignments generated in the research we have surveyed were limited to linking of a single entity of a source ontology to a single entity of a target ontology. The links lack expressiveness to a large extent. In order to better express the relationships between entities from different ontologies, they require rather full fledged axioms, as pointed out in [12, 67]. In the example from [12], a complex correspondence states that the professions are modeled as instances of the class

[32]http://oaei.ontologymatching.org/2020/

[33]http://www.loa.istc.cnr.it/old/ontologies/DLP_397.owl

[34]http://www.ontologydesignpatterns.org/ont/dul/DUL.owl

Profession in PROTON, and the single entity of DBPedia is matched to an expression in PROTON which restricts the property *hasProfession* to the value of the profession of interest. However, generating complex correspondences is still an open challenge in the ontology matching field in general.

The most significant issue in ontology matching is that most ontologies lack definitions of terms in logic, comparable to the completeness of natural language definitions in dictionaries. Most of the intended semantics of terms are left to the intuition of humans reading their names. Until richer definitions become the norm, ontology matching, whether manual or automatic, will remain difficult to conduct or evaluate.

7.7. *Multilingualism*

Very few foundational ontologies are equipped with lexical layers in languages other than English (e.g., BFO has been enriched with a lexical annotation in Portuguese, SUMO is the exception and is matched to the 26 languages in Open Multilingual WordNet [7]). However, with the increasing amount of multilingual data on the Web and the consequent development of ontologies in different languages, foundational ontologies should also be equipped with richer multilingual annotations in order to facilitate the multilingual and cross-lingual ontology matching tasks.

8. Final remarks

Ontology matching has reached some maturity in terms of matching domain ontologies. There is however room for further developments in the adoption of foundational ontologies in the task. Systematically enriching domain ontologies with foundational ones would also promote their use as semantic bridges in the task of matching domain ontologies. One of the difficulties however is the need of specialised knowledge as injecting foundational ontologies in ontology matching, in general, requires deeply understanding the foundational concepts and its relations. Another issue concerns the lack of formal definitions associated to lexicons (comments and labels) helping to understand the precise semantics of each concept. These are among the main brakes to automatising together with the points discussed above.

This paper has provided an overview of the adoption and exploration of foundational ontologies in the task of ontology matching, on different perspectives: work attempting to compare and match foundational ontologies, natural language definitions vs logical statement issues addressed by linking lexicons and foundational ontologies, the role of foundational ontologies as bridges for linking domain ontologies; and equipping existing domain ontologies with foundational distinctions. We have pointed out the limitations to be addressed in order to bring the clarity of semantics of foundational ontologies in ontologies in general.

In a broader scope, semantic web in general and its materialisation with the linked open data initiative still lack such ontological distinction, as recently stated in [3, 87]. This has been further corroborated in [5], where it is stated that in the semantic web, there is an increasingly need for serious engagement with ontology, understood as a general theory of the types of entities and relations making up their respective domains of inquiry. However, there is still little interaction between the communities, despite the fact that they share common ambitions in terms of knowledge understanding. This goes beyond the matching task as discussed in this paper in the sense that is has to take into account the data being described by the ontologies.

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