Semantic Precision and Recall for Evaluating Incoherent Ontology Mappings

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Abstract. Ontology mapping plays an important role in the Semantic Web, which generates correspondences between different ontologies. Usually, precision and recall are used to evaluate the performance of a mapping method. However, they do not take into account of the semantics of the mapping. Thus, semantic precision and recall are proposed to resolve the restricted set-theoretic foundation of precision and recall. But the semantic measures do not consider the incoherence in a mapping which causes some trivialization problems. In this paper, we propose semantic measures for evaluating *incoherent ontology mappings*. Specifically, a general definition of semantic measures is given based on a set of formal definitions capturing reasoning with incoherent mappings. Then we develop a concrete approach to reasoning with incoherent mappings, which results in some specific semantic measures. Finally, we conduct experiments on the data set of conference track provided by OAEI[1].

1 Introduction

Ontology mapping plays an important role in the Semantic Web to solve heterogeneous problems between semantically presented data sources. So far, many ontology mapping algorithms have been developed (see surveys in [17,2,18]). With the increasing number of ontology mapping algorithms, some evaluation measures have been used to compare them, such as precision and recall [3]. These measures compare a mapping provided by a mapping algorithm with a reference mapping on syntactic level without considering the semantics of the mapping. Here, a reference mapping is usually created by domain experts and is reliable. To deal with this problem, Euzenat proposes the semantic precision and recall in [5], where a mapping is evaluated in a semantic way.

Recently, there is an increasing interest in dealing with logical contradictions caused by mappings (see [15] and [16] for examples). In some of these work, an ontology mapping is translated into description logic (DL) axioms. This treatment of an ontology mapping is useful for ontology integration [11], mapping

[1] OAEI indicates ontology alignment evaluation initiative, which is a platform to evaluate various ontology mapping systems.

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revision [16], mapping debugging [15] and mapping evaluation [12,14]. In these scenarios, ***incoherence***[2] of a mapping is usually an unavoidable problem. As reported in [6] about the results in OAEI, more than 80% analyzed mappings are incoherent for most of the mapping systems.

Although incoherence is different from inconsistency[3] as an incoherent ontology can be consistent, we also encounter some trivialization problems because of the explosive problem of inconsistency (i.e. everything can be inferred from an inconsistent ontology): first, an unsatisfiable concept is a sub-concept of any concept; second, an unsatisfiable concept is equivalent to any other unsatisfiable concept. Thus, when defining a semantic measure for an incoherent mapping, we cannot apply standard DL semantics as it will result in counter-intuitive results.

In order to overcome the trivialization problems, we provide a set of formal definitions capturing reasoning with incoherent mappings. Based on these definitions, we then give a general definition of semantic precision and recall. To instantiate the general semantic measures, one concrete approach to reasoning with incoherent mappings is proposed. The key benefit of our incoherent-tolerant approach is that, every correspondence which is inferred by using our approach can be explained in a meaningful way. That is to say, for each such correspondence c, we can find a coherent subset from the merged ontology to infer c. This coherent subset can be served as a justification of c from the merged ontology.

2 Preliminaries

We introduce the notions of an unsatisfiable concept and incoherence in a DL-based ontology defined in [9]. More details about Description Logics (DLs for short) can be found in the DL handbook [1].

Definition 1. ***(Unsatisfiable Concept)*** *A named concept C in an ontology O is unsatisfiable iff for each model $\mathcal{I}$ of O, $C^{\mathcal{I}} = \emptyset$. Otherwise C is satisfiable.*

This definition means that a named concept is unsatisfiable in an ontology O iff the concept is interpreted as an empty set by all models of O.

Definition 2. ***(Incoherent Ontology)*** *An ontology O is incoherent iff there exists at least one unsatisfiable concept in O. Otherwise O is coherent.*

Given two ontologies O_1 and O_2, we can define correspondences.

Definition 3. ***(Correspondence)****[7] Let O_1 and O_2 be two ontologies, Q be a function that defines sets of mappable elements $Q(O_1)$ and $Q(O_2)$. A correspondence is a 4-tuple $\langle e, e', r, \alpha \rangle$ such that $e \in Q(O_1)$ and $e' \in Q(O_2)$, r is a semantic relation, and $\alpha \in [0, 1]$ is a confidence value. A mapping consists of a set of correspondences.*

[2] A mapping is incoherent if there is a concept in the merged ontology which is interpreted as an empty set and no such concepts exist in the single ontologies.

[3] A mapping is inconsistent if the merged ontology is inconsistent and two single ontologies are consistent. An ontology is inconsistent iff. there is no model in the ontology.

There is no restriction on function Q and semantic relation r. The mappable elements $Q(O)$ could be concepts, object properties, data properties and individuals. As for the semantic relations, we mainly consider the equivalence relation and subsumption relation. A mapping is a set of correspondences whose elements are mappable. The correspondences can be divided into two categories:

Definition 4. ***(Complex/Non-Complex Correspondences)****[8] A correspondence $c = \langle e, e', r, \alpha \rangle$ is non-complex if both e and e' are atomic concept names or property names in the corresponding aligned ontologies. Otherwise c is complex.*

In this paper, we only consider those non-complex correspondences to focus on the explanation of our semantic measures. Note that, most of the existing ontology mapping algorithms or systems generate non-complex mappings [8].

Definition 5. ***(Mapping Semantics)****[13] Given a mapping $\mathcal{M}$ between ontologies O_1 and O_2. A correspondence $\langle e, e', r, \alpha \rangle \in \mathcal{M}$ can be converted to a DL axiom in this way: $t(\langle e, e', r, \alpha \rangle) = ere'$, where t is a translation function. $t(\mathcal{M}) = \{t(c) : c \in \mathcal{M}\}$.*

Take a correspondence $c = \langle SocialEvent, Document, \sqsubseteq, 1.0 \rangle$ as an example. We have $t(c) = SocialEvent \sqsubseteq Document$. For convenience, $O_1 \cup_{\mathcal{M}} O_2$ is used to indicate the merged ontology $O_1 \cup O_2 \cup t(\mathcal{M})$.

Definition 6. ***(Incoherent mapping)****[13] Assume we have two ontologies O_1 and O_2 and a mapping $\mathcal{M}$ between them. $\mathcal{M}$ is incoherent with O_1 and O_2 iff there exists a concept C in O_i with $i \in \{1, 2\}$ such that C is satisfiable in O_i and unsatisfiable in $O_1 \cup_{\mathcal{M}} O_2$. Otherwise, $\mathcal{M}$ is coherent.*

Definition 6 is given based on a consistent merged ontology. The incoherence of a mapping most occurs when matching ontologies on terminological level.

3 Formal Definitions

3.1 Reasoning with Incoherent Mappings

To cope with the trivialization problems in a mapping, we define the meaningfulness of an incoherency reasoner which is inspired by the notion of meaningfulness of an inconsistency reasoner given in [10]. An inconsistency reasoner is one which can reason with inconsistent ontologies, without relying on a repair of the inconsistencies in the ontologies. Namely, an inconsistency reasoner can return meaningful answers, without suffering from the explosive problem in the classical reasoning (i.e, any statement is a consequence of an inconsistent knowledge base). Similarly we define an incoherency reasoner as one which can reason with incoherent ontologies without relying on a repair of the incoherency in the ontologies. That is, an incoherency reasoner can return meaningful answers, without suffering from the trivialization problems caused by unsatisfiable concepts in the classical reasoning.

Definition 7. ***(Meaningfulness)*** *Assume we have two ontologies O_1 and O_2 and a mapping $\mathcal{M}$ between them. For a non-complex correspondence $c = \langle e, e', r, \alpha \rangle$, an answer provided by an incoherency reasoner is meaningful iff the following condition holds:*

$$\Sigma \Vdash t(c) \Rightarrow$$
$$(\exists \Sigma' \subseteq \Sigma)(\Sigma' \not\models e \sqsubseteq \bot \;\; and \;\; \Sigma' \not\models e' \sqsubseteq \bot \;\; and \;\; \Sigma' \models t(c)),$$

where $\Sigma = O_1 \cup_{\mathcal{M}} O_2$. An incoherency reasoner is regarded as meaningful iff all of the answers are meaningful.

In this definition, t is a translation function (see Definition 5). This definition indicates that, for a non-complex correspondence c, if $t(c)$ can be inferred from an incoherent set Σ then there exists a subset Σ' of Σ such that Σ' is coherent w.r.t. c and Σ' can infer $t(c)$ using classical reasoning. Here, we say Σ' is coherent w.r.t. c, if e and e' are satisfiable in Σ'. Definition 7 implies that an incoherency reasoner performs as a classical reasoner if Σ is coherent w.r.t. c.

In Definition 7, we only ensure that the signatures appearing in c are satisfiable in Σ'. This means there may exist some other unsatisfiable entities in Σ' and thus Σ' is still incoherent. Since our aim is to avoid the trivial inference for c, we do not care about other unsatisfiable concepts. In our view, it is reasonable to have other unsatisfiable entities in Σ' as repairing a mapping is not our aim.

As completeness and soundness are two main properties of a reasoner, we analyze them for our reasoner according to the definitions given in [10].

Definition 8. ***(Local completeness)*** *For a non-complex correspondence c, an incoherency reasoner is locally complete w.r.t. a coherent subset Σ' w.r.t. c of Σ ($\Sigma = O_1 \cup_{\mathcal{M}} O_2$) iff the following condition is satisfied:*

$$\Sigma' \models t(c) \Rightarrow \Sigma \Vdash t(c).$$

Namely, if $t(c)$ can be inferred from the given coherent subset Σ' w.r.t. c by applying a standard DL reasoner, it should be also inferred by Σ by using the incoherency reasoner.

Definition 9. ***(Local soundness)*** *For a non-complex correspondence c, an answer to a query $\Sigma \Vdash t(c)$ is regarded as locally sound w.r.t. a subset $\Sigma' \subseteq \Sigma$ ($\Sigma = O_1 \cup_{\mathcal{M}} O_2$) which is coherent w.r.t. c, iff the following condition is satisfied:*

$$\Sigma \Vdash t(c) \Rightarrow \Sigma' \models t(c).$$

That is, if $t(c)$ can be inferred by using our reasoner, it should be implied by the given coherent subset Σ' w.r.t. c by applying a standard DL reasoner.

3.2 Semantic Precision and Recall

With the introduction of the definitions that an incoherency reasoner should fulfill, we can adapt the required notations in [5] to define our semantic measures.

Definition 10. ***(α-Consequence of a mapping)*** *Given a mapping $\mathcal{M}$ between two ontologies O_1 and O_2, a correspondence c is an α-consequence of O_1, O_2 and $\mathcal{M}$ iff we have*

$$O_1 \cup_{\mathcal{M}} O_2 \Vdash t(c).$$

This also can be written as $\mathcal{M} \Vdash_{O_1,O_2} c$.

Definition 11. ***(Closure of a mapping)*** *Given a mapping $\mathcal{M}$ between two ontologies O_1 and O_2, the closure of the mapping, denoted as $Cn^{Inco}(\mathcal{M})$, can be defined as the following:*

$$Cn^{Inco}(\mathcal{M}) = \{c|\mathcal{M} \Vdash_{O_1,O_2} c\}.$$

That is, the closure of a mapping is the set of all α-consequences.

Definition 12. ***(Semantic precision and recall)*** *Given a reference mapping $\mathcal{R}$, the semantic precision of some mapping $\mathcal{M}$ is defined as below:*

$$P^{Inco}_{sem}(\mathcal{M}, \mathcal{R}) = \frac{|\mathcal{M} \cap Cn^{Inco}(\mathcal{R})|}{|\mathcal{M}|} = \frac{|\{c \in \mathcal{M} : \mathcal{R} \Vdash_{O_1,O_2} c\}|}{|\mathcal{M}|}.$$

The semantic recall is defined by

$$R^{Inco}_{sem}(\mathcal{M}, \mathcal{R}) = \frac{|Cn^{Inco}(\mathcal{M}) \cap \mathcal{R}|}{|\mathcal{R}|} = \frac{|\{c \in \mathcal{R} : \mathcal{M} \Vdash_{O_1,O_2} c\}|}{|\mathcal{R}|}.$$

Now we discuss some properties of the semantic measures defined in [5]. First, it is obvious that P^{Inco}_{sem} and R^{Inco}_{sem} satisfy *positiveness*, *completeness-maximality* and *correctness-maximality*. The property of positiveness means the values of semantic measures are no less than zero. Completeness-maximality is a property to indicate that the value of the recall is 1 if all correspondences in $\mathcal{R}$ can be inferred by $\mathcal{M}$. Similarly, the property of correctness-maximality shows that we know that the value of the precision is 1 if all correspondences in $\mathcal{M}$ can be inferred by $\mathcal{R}$. Second, our semantic measures may not satisfy the property *boundedness*. This property means the values of semantic measures should be no less than those values obtained by using standard measures without considering semantics. Take $R^{Inco}_{sem}(\mathcal{M}, \mathcal{R})$ as an example. If $\mathcal{M}$ is incoherent, a correspondence $c \in \mathcal{M}$ may not be included in $Cn^{Inco}(\mathcal{M})$ if we fail to find a coherent subset Σ' w.r.t. c such that $\Sigma' \models t(c)$. That is, we may not always have $\mathcal{M} \subseteq Cn^{Inco}(\mathcal{M})$ and thus the boundness w.r.t. R^{Inco}_{sem} may not hold.

4 Concrete Approach to Reasoning with Incoherent Mappings

From Section 3 we can see that reasoning with incoherent mappings is vital for our definitions of semantic measures. Here, we propose a novel approach to reasoning with an incoherent mapping based on selection functions. This

Algorithm 1: The algorithm to compute $\mathcal{M} \Vdash_{O_1,O_2} c$

Data: Two ontologies O_1 and O_2, a mapping $\mathcal{M}$ between the two ontologies, and a non-complex correspondence $c = \langle e_1, e_2, r, \alpha \rangle$.
Result: Boolean value

1 **begin**
2     $\Sigma \leftarrow O_1 \cup_{\mathcal{M}} O_2$;
3     $\Sigma' \leftarrow \emptyset$;
4     $k \leftarrow 0$;
5   **if** $t(c) \in \Sigma$ **then**
6   **return** *true*
7   **while** $s_k(\Sigma, t(c)) \neq \emptyset$ **do**
8         $\Sigma' \leftarrow \Sigma' \cup s_k(\Sigma, t(c))$;
9   **if** $\Sigma' \models e_1 \sqsubseteq \bot$ *or* $\Sigma' \models e_2 \sqsubseteq \bot$ **then**
10             $\Sigma' \leftarrow \Sigma' \setminus s_k(\Sigma, t(c))$;
11   **for** $ax \in s_k(\Sigma, t(c))$ **do**
12                 $\Sigma' \leftarrow \Sigma' \cup \{ax\}$;
13   **if** $\Sigma' \models e_1 \sqsubseteq \bot$ *or* $\Sigma' \models e_2 \sqsubseteq \bot$ **then**
14                     $\Sigma' \leftarrow \Sigma' \setminus \{ax\}$;
15   **if** $\Sigma' \models t(c)$ **then**
16   **return** *true*
17         $k \leftarrow k + 1$;
18   **return** *false*
19 **end**

approach (see Algorithm 1) is proposed based on the linear extension strategy in [10] which uses selection functions. Unlike the approach given in [10], ours deals with incoherence instead of inconsistency. Besides, two heuristic strategies have been exploited to improve the efficiency.

Algorithm 1 takes ontologies O_1 and O_2, a mapping $\mathcal{M}$ between them and a correspondence c as inputs and outputs whether c can be inferred by $\mathcal{M}$ based on a relevance-directed selection function s. An axiom is directly relevant to another axiom if they share at least one signature[4]. An axiom is directly relevant to a set S of axioms if this axiom is directly relevant to an axiom in S. $s_k(\Sigma, t(c))$ indicates a set of axioms which are directly relevant to $s_{k-1}(\Sigma, t(c))$ $(k > 0)$ and $s_0(\Sigma, t(c))$ includes those axioms which are directly relevant to $t(c)$.

In the approach, we first check whether c is explicitly included in $\mathcal{M}$ (see Line 5) to improve the reasoning efficiency. If not, the approach iterates on the sets of selected axioms and terminates if the current set of selected axioms s_k is empty (see Line 7) or if $t(c)$ can be inferred (see Line 15). For each iteration, if adding the current $s_k(\Sigma, t(c))$ to Σ' makes the modified Σ' incoherent w.r.t. c, then we check the axioms in $s_k(\Sigma, t(c))$ one by one. In this way, those relevant axioms are kept for reasoning as many as possible.

It is easy to check that the incoherency reasoner based on Algorithm 1 satisfies meaningfulness, local soundness and local completeness. Besides, the semantic measures defined by this approach satisfy the property of boundedness. This is because for an incoherent mapping $\mathcal{M}$, any $c \in \mathcal{M}$ can be inferred by $Cn(\mathcal{M})$ and thus we have $\mathcal{M} \subseteq Cn(\mathcal{M})$. So the boundedness property is satisfied.

[4] A signature means an atomic concept name, property name or individual name.

5 Experimental Evaluation

Our measures have been implemented using OWL API 3.0.0 and the standard reasoning tasks are performed using Pellet[5]. Our experiments were performed on a laptop with 2.13 GHz Intel(R) Core(TM) i3 CPU and 2.00 GB of RAM using Windows 7. Sun's Java 1.6.0 was used for Java-based tools and the maximum heap space was set to 1GB. When evaluating a mapping by applying a specific evaluation method, the timeout is set to 30 minutes.

In this section, we compare our measures (marked as "SF-based approach") with those without considering semantics (marked as "No semantics") and the semantic measures [5] defined by a standard DL reasoner (marked as "DL semantics"). We also compare various mapping systems by applying different measures.

5.1 Data set

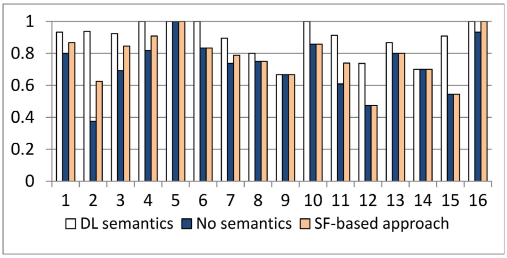
We use the data set in the conference track provided by OAEI 2009. It consists of a set of expressive ontologies, the reference mappings and the mappings generated by the mapping systems which have participated in the contest (see [6] for more details). For our tests, we choose those ontology pairs whose corresponding reference mappings are available. In this way, 16 out of 21 reference mappings are selected which involve 16 ontology pairs and 7 individual ontologies. Among these selected individual ontologies, ontology edas has 624 axioms and the sizes of other ontologies vary from 116 to 354. The ontology pairs are listed as followings: 1: cmt-conference, 2: cmt-confOf, 3: cmt-edas, 4: cmt-ekaw, 5: cmt-iasted, 6: cmt-sigkdd, 7: confOf-edas, 8: confOf-ekaw, 9: confOf-iasted, 10: confOf-sigkdd, 11: edas-ekaw, 12: edas-iasted, 13: edas-sigkdd, 14: ekaw-iasted, 15: ekaw-sigkdd, 16: iasted-sigkdd. The participated systems provide mapping results for all of the selected ontology pairs. All participated systems can be seen in Figure 1.

Notes: (1) We do not consider the correspondences between a data property and an object property as we pay more attention to the explanation of our evaluation approaches. (2) The individuals in ontologies iasted and edas have been removed since they cause inconsistency in some merged ontologies and we currently only focus on dealing with incoherence. (3) Those correspondences whose confidence values are no less than 0.2 are regarded as correct. (4) Both of the systems AgrMaker and aroma generate 93.75% incoherent mappings. As for system ASMOV, only 6.25% incoherent mappings are generated. For others, all of the generated mappings between the selected ontology pairs are incoherent.

5.2 Comparison of Various Evaluation Methods

To compare various evaluation measures, we choose the mapping results generated by the system kosimap. Because this system provides more interesting results which contain more correspondences associated with distinct confidence values.

[5] http://clarkparsia.com/pellet/



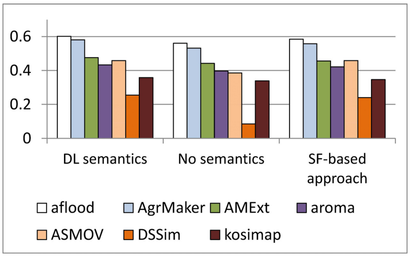


Fig. 1. The left figure shows the performance of various evaluation measures w.r.t. the recall over the mappings generated by the system kosimap. The figure on the right shows the comparison of different mapping systems w.r.t. the average f-measures.

The figure on the left in Figure 1 shows the performance of various evaluation methods to compute the recalls. From the figure, we first observe that the standard recall (i.e. "No semantics") always returns the lowest value. This can be explained by the fact that the semantic recalls defined by DL semantics and our approach satisfy the boundedness property. Second, the values returned by the semantic recall defined by DL semantics are no less than those returned by that defined by our approach. It is because DL semantics suffers from the trivialization problems, thus many meaningless correspondences can be inferred. Finally, we can observe that the difference between the values returned by the two semantic recalls is obvious. The average value of the difference is 0.15. Besides, the largest one is 0.36 for the mapping between ekaw and sigkdd. It shows us that many meaningless correspondences have been inferred by the approach using DL semantics when computing semantic recalls.

Similarly, we can analyze the results with respect to the precisions. First, we can see that the same values are returned by the semantic precisions for all reference mappings except the mapping between ontologies edas and iasted which is incoherent. Second, the values returned by the semantic precisions are no less than the value returned by the standard precision as the semantic precisions also satisfy the boundedness property.

5.3 Comparison of Mapping Systems

To compare different mapping systems using our measures, all selected ontology pairs except the pairs edas-iasted and iasted-sigkdd are considered as our approach fails to return recall values for some mappings between the two pairs within the time limit. The figure on the right in Figure 1 shows the comparison of various mapping systems w.r.t. the average f-measure. Here, f-measure is a harmonic mean (i.e. $\frac{2*precision*recall}{precision+recall}$) of precision and recall.

Obviously, different semantic measures produce similar values for a specific system. Take system aflood as an example. The average values are 0.602 and 0.585 returned by the f-measures defined by DL semantics and ours respectively. This is because the precisions always produce the same values and the difference among the recall values is not very big although it is obvious.

We can also see that different approaches to compute f-measures rank the systems differently. This is mainly caused by the positions of the systems AMExt, aroma and ASMOV. It maybe because that the percentage of implied correspondences in a mapping generated by ASMOV is higher than that generated by aroma. Thus the ordering of the two systems is changed when the evaluation approaches vary from the standard approach to the approach using DL semantics.

6 Related Work

Many measures have been proposed to evaluate ontology mappings in the literature. Here, we focus on those measures related to precision and recall.

As the standard measures are sensitive to the syntactics of a mapping, a general framework has been proposed in [4]. The framework are instantiated by three different measures considering some particular aspects of mapping utility based on the proximity of correspondence sets. The weakness of these measures is that they do not take the semantics of the ontologies into account.

Due to the restricted set-theoretic foundation of the traditional precision and recall, Euzenat defined semantic measures in [5], where a first-order model theoretic semantics is adopted. The semantic measures are proposed using the deductive closure bounded by a finite set. However, their measures are not tailored to evaluate incoherent mapping.

In [8], a simplified version of semantic precision and recall has been proposed. This restricted version defines the semantics of mappings according to a translation into a logical theory in [13]. Comparing their work, we use the same mapping semantics but different formulas to compute precision and recall. Another difference is that the measures defined in [8] do not deal with incoherence.

In [12], the proposed quality measures consider the number of unsatisfiable concepts and the effort to repair an incoherent mapping separately. The main difference between this work with ours is that, we consider the logic implication to see whether a correspondence can be inferred or not, where every correspondence inferred by using our approach can be explained in a meaningful way.

7 Conclusion and Future Work

In this paper, we proposed some novel semantic precision and recall for evaluating incoherent ontology mappings. We first provided a set of formal definitions which capture reasoning with incoherent mappings. Based on these definitions, we gave a general definition of semantic precision and recall. Then we proposed a concrete incoherence-tolerant reasoning approach based on selection functions, which results in a pair of specific semantic precision and recall. Finally, our experimental results showed that our measures are promising to evaluate incoherent mappings which ensures each correspondence inferred by using our approach can be explained in a meaningful way. This guarantee has been implemented by finding a coherent subset w.r.t. a correspondence using our approach.

In the future, we will extend our work to evaluate inconsistent ontology mappings and develop new methods to improve the efficiency of our approach. Besides, more data sets will be considered.

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