Compatible and Incompatible Ontology Mappings

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Abstract. Upper ontologies are interesting because describing and representing concepts that can be used across various domains (as opposed to domain ontologies). This feature may enable increased correctness of mappings between domain ontologies, conceptual schema and languages. Unfortunately, there exist various upper ontologies and it is quite difficult to decide or to assess which of them should be used in one application: the main reason is that upper ontologies are complex artifacts possibly specified in specific logics providing formalization of highly abstract concepts. Researchers have been therefore interested in understanding the similarities between upper ontologies by establishing mappings between key ontology concepts. In this paper, we review mappings proposed in literature and we establish a notion of compatibility between these mappings by introducing a method based on Galois connections. We then conclude with a synthesis of the results obtained by using the proposed method. The key findings put in evidence some key differences leading to incompatibility among proposed mappings. These differences are worth to be further investigated.

Keywords: Upper ontologies, Ontology mappings, Galois connection

1 Introduction

In literature, what can be referred to as mappings between ontologies has been studied in various contexts, especially in the case of domain ontologies. Mappings are usually abstract or concrete functions or relations between ontology artifacts (often concepts); mappings correspond to, precise or approximate, similarities, equality, subsumption [1]. Mappings have been discussed and formalized in domain ontology matching, alignment and merging; distinct approaches have been then proposed based on logics [2], categories [3], argumentations , [4], and practice [5]. All these approaches require to use a specific formalization and not really usable for upper ontologies because mainly requiring description logics and/or, not very generic, easily understandable, concepts belonging to ontologies). Some of those approaches are focusing on the mapping correctness, trying to understand if a mapping is not logically contradictory when combined with the whole set of ontology axioms while some other approaches focuses on what we name mapping acceptability, i.e. looking for mappings that, according to formulated arguments, are more suitable than others.

We undertake an intermediate approach base on the key notion of *mapping compatibility and incompatibility*. Mappings are incompatible if they cannot be used consistently together in one single application. However, it is quite important to note that two incompatible mappings may be both correct (w.r.t. the whole set of ontology axioms). Compatible and incompatible mappings are relevant at both run-time and design time. At run-time, compatible and incompatible mappings are especially relevant in peer to peer applications, distributed applications and agent based applications and finally open interoperability focused applications. Indeed, all of such applications often comprise several autonomous entities without any central point of control and even without any common management procedure: each of these entities may use its own vocabulary, reference schema, ontology and so on to map each message, flow, variables and so on coming from other entities. At design-time, compatible and incompatible mappings can be used to understand distinct perspectives underlying interpretations of ontological artifacts. For instance, to accomplish alignment, one concept can be mapped on to another concept belonging to another ontology due to label based similarities (and therefore the mapping is quite loose) while another mapping can map one concept on to another one because their logical equivalence (within some theoretical frameworks) can be established. Within the former mapping, the various ontological artifacts (as concepts) are interesting because of their labels; within the second mapping, the various ontological artifacts are interesting as logical artifacts (to perform for instance, reasoning).

Throughout the paper, we therefore provide a complete method for checking mapping incompatibility, especially in the case of upper ontologies. We consider this notion very useful whenever there ontologies are formalized in distinct logics and whenever the key point is not to evaluate if a mapping is correct but just if distinct mappings can be used together (because they are not contradictory). Therefore, mapping compatibility and incompatibility will be formalized by using mechanisms which are logic-independent (as for instance, the case of e-connections [6]).

1.1 Motivating Example

We have two agents α and γ, they are using ontologies as their knowledge base. First agent is based on DOLCE ontology and the second agent is based on GFO ontology and they have ontology mappings for others agent's ontology. These ontology mappings are independent to each other, i.e., these mappings may have different ontology correspondences for any concept. Fragment of DOLCE Ontology O_1 is as follows

$$Endurant \sqsubseteq Particular$$
$$Perdurant \sqsubseteq Particular$$
$$Event \sqsubseteq Perdurant$$
$$Stative \sqsubseteq Perdurant$$
$$Process \sqsubseteq Stative$$
$$State \sqsubseteq Stative$$

And Fragment of GFO Ontology O_2 is as follows

$$Abstract \sqsubseteq Individual$$

$$Concrete \sqsubseteq Individual$$
$$Occurrent \sqsubseteq Concrete$$
$$Process \sqsubseteq Occurrent$$
$$Descrete\ Process \sqsubseteq Process$$
$$Change \sqsubseteq Occurrent$$
$$Process \sqcap Change \sqsubseteq \perp$$

Fragment of Alignment M_A of ontologies O_1 and O_2 is as follows

$$(O_1{:}\,Particular, O_2{:}\,Individual)$$
$$(O_1{:}\,Event, O_2{:}\,Change)$$

Fragment of Alignment M_B of ontologies O_1 and O_2 is as follows

$$(O_1{:}\,Particular, O_2{:}\,Individual)$$
$$(O_1{:}\,Event, O_2{:}\,Discrete\ Process)$$

Agent α is based on Ontology O_1 and has alignment M_A, while Agent γ is based on ontology O_2 and has alignment M_B. Agent α sends two messages to Agent γ: a) msg(Particular) b) msg(Event). We have to check whether the ontology artifacts used in these messages are interpreted by the receiving agent are compatible with the sent messages. For this we have to check whether the ontology correspondences for these ontology artifacts are compatible in mappings M_A and M_B. For msg(Particular) both alignments have compatible mappings for this message because they are same, while for msg(Event) both alignments have incompatible mappings for this message because the mapped concepts are disjoint and nothing common between them.

This paper is structured as follows. In the next section we describe about Galois connections and Ontology mapping compatibility and incompatibility and we present a table about available upper ontology mappings. We present our proposed method in Section 3. A synthesis of our work is presented in Section 4. We then present Related Work in 5. Finally we conclude in Section 6.

2 Preliminaries

In this section we will describe about Galois connections and Ontology mapping compatibility and incompatibility.

2.1 Galois connections

In the literature, two definitions of Galois connections are reported.

Definition 1: Given ordered structures A, B with partial order relationship $\preccurlyeq$and antitone mappings $\alpha: A \rightarrow B$ and $\gamma: B \rightarrow A$, we say that the pair (α, γ) establishes an *order reversing Galois connection* between A and B if $b \preccurlyeq \alpha(a)$ and $a \preccurlyeq \gamma(b)$, $\forall a \in \alpha, and\ b \in \gamma$.

Definition 2: Given ordered structures A, B with partial order relationship $\preccurlyeq$ and isotone mappings $\alpha : A \rightarrow B$ and $\gamma : B \rightarrow A$, we say that the pair (γ, α) establishes an *order preserving Galois connection* between A and B if $\alpha(a) \preccurlyeq b$ and $a \preccurlyeq \gamma(b)$, $\forall a \in \alpha, and\ b \in \gamma$.

The first definition can be seen as symmetric where the two mappings γ and α cannot be differentiated; if order relationships are information orders then if a $\succcurlyeq_A$ b this means that a is less informed than b (the same as for instance in subsumption); γ and α can be interpreted *abstraction mappings*, because applying one mapping result in some information loss. The second definition is not symmetric because γ and α can be differentiated; under the same interpretation of order relationships, α is an *abstraction mapping* while γ is a *concretization mapping* because resulting in information enrichment.

Galois connections are interesting whenever dealing with mappings between ontologies because at least:

1. Independent of the kind of formalization (such as the kind of logics) used to represent ontologies, ontologies comprise at least one taxonomy to organize artifacts, which corresponds to an information order as well;
2. Can be applied to concepts but also to relationships/properties [7] and to their taxonomies.

2.2 Ontology mapping incompatibility and compatibility

Except approximated mappings, precise mappings between ontologies are basically represented as functions or relationships between ontology artifacts. Representing mappings as relationships enables to map one artifact on to several artifacts, which is the position we are undertaking in the remainder. Let now suppose that O_1, O_2 are two ontologies and C_1, C_2 are the sets of their concepts, ordered according to concept taxonomies. Starting from two concept mappings $f \subseteq C_1 \times (C_2 \cup \{\perp\})$, $g \subseteq C_2 \times (C_1 \cup \{\perp\})$, being $\perp$ used to complete the two ontology mappings f and g whenever they are undefined. The same can be done for relationships/properties defined in the ontologies. Starting from mappings, for building functions on ordered sets as required by Galois connection, lets now define orders in power sets 2^{C_1} and 2^{C_2} in the same way as follows:

$V \preccurlyeq W$ iff $\{C \in C_i | S \in V$ and $C \sqsubseteq_i S\} \subseteq \{C \in C_i | S \in W$ and $C \sqsubseteq_i S\}$ where $\sqsubseteq_i$ represents the concept taxonomies in C_i.

Two functions can then be easily defined as:

$$\alpha: 2^{C_1} \rightarrow 2^{C_2}$$
$$\gamma: 2^{C_2} \rightarrow 2^{C_1}$$

with $\alpha(\{c_i\}) = \{s_j | (s_j, c_i) \in f\}$ and $\gamma(\{c_i\}) = \{s_j | (s_j, c_i) \in g\}$.

Functions α, γ may or may not respect conditions required in definitions 1 and 2. Figures 1(a) to 1(d) show the relevant situations depending on the conditions required for Galois connections. Each situation depicted in the figures can be associated with a logical meaning (according to [8] as better explained in the remainder), which is based on the fact that the ontology source of one mapping may be re-interpreted in the ontology target of the same mapping.

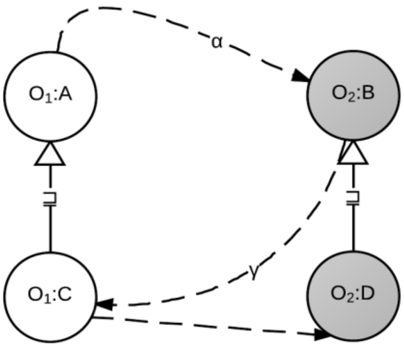

Fig. 1.a

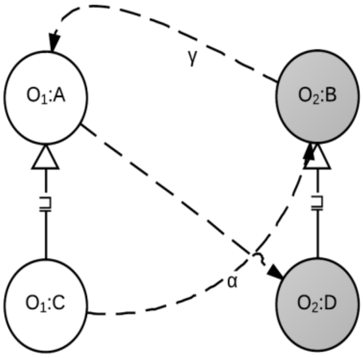

Fig. 1.b

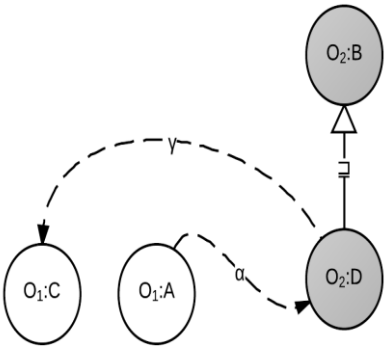

Fig. 1.c

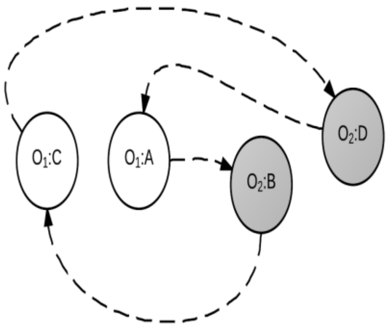

Fig. 1.d

Fig. 1.a provides the situation of an order preserving the Galois connection. It can be shown that A,B,C,D (for instance, concepts) are interpreted as first order logics symbols, α (and f mapping by definition) leads to necessary conditions for O_1 being interpreted into O_2 (a function α is said to be an interpretation of O_1 into O_2 iff O_1 is satisfied in all models of O_2, by interpreting each symbol 's' of O_1as models of $\alpha(s)$. This means that O_2 allows to infer at least the same formulas then $O_1$when substituting symbols A, C with B and D (for instance, it is possible to infer $A \sqsubseteq_{O1} C$ because $B \sqsubseteq_{O2} D$). Because α and γ are symmetric, γ also leads to necessary conditions for O_2being interpreted into O_1. Fig. 1.b corresponds to the situation of an order reversing Galois connection. By interpreting A,B,C,D as first order logic symbols, it is possible to define an interpretation of O_1 into O_2 such that $\alpha'(\{A \dots\}) = \{\neg B, \dots\}$ and $\alpha'(\{C \dots\}) = \{\neg D, \dots\}$ ($\neg$ is a negation connective). In practice, it is a negative interpretation saying what is not instead of what is. Fig. 1.c depicts one acceptable situation in which Galois connection conditions are not satisfied. In this case, α is an interpretation of O_1into O_2, but O_2cannot be interpreted in $O_1$by γ therefore, f and g mappings (on which α and γ are built) are fundamentally distinct. Finally, Fig. 1.d depicts another acceptable situation in which Galois connection conditions are not satisfied. In this case, α and γ bound concepts in completely distinct and independent

way. For instance, α interprets A as B, therefore what is satisfied by B should be satisfied in O_1 by A. Vice versa, γ interprets B as C, therefore what is satisfied by C should be also satisfied by B in O_2. Mappings f and g convey two distinct and independent interpretations (without considering those concepts may be proved equivalent).

According to the discussion above, the notion of "mapping incompatibility" can now be introduced by the following definition.

Definition 3. Two mappings f and g between two ontologies are "compatible" iff the corresponding functions α and γ are either an order preserving Galois connection or an order reversing Galois connection. Two mappings that are not compatible are said to be "incompatible".

It should be noted that "mapping incompatibility" and "mapping compatibility" are distinct notions that "mapping correctness" mentioned in the Introduction. Indeed, compatible or incompatible mappings can be either correct or incorrect when combined with additional ontology axioms.

Compatibilities and incompatibilities can also be stated at the level of ontology artifacts according to the following definition.

Definition 4. Given mappings f and g, functions α and γ built as above, an ontology artifact A is compatible with ontology artifacts $\alpha(\{A\})$ iff Galois connections conditions are respected between A and $\alpha(\{A\})$. Symmetrically, an ontology artifact B is compatible with ontology artifacts $\gamma(\{B\})$ iff Galois connections conditions are respected between B and $\gamma(\{B\})$. Otherwise involved artifacts are incompatible.

2.3 Existing upper Ontology Mappings

Comparing upper ontologies is usually performed by establishing (explicitly or implicitly) some mappings between concepts belonging to distinct ontologies. We have defined a methodology for collecting existing mappings (Table 1), then for analyzing them according to Galois connections.

Source	WordNet	DOLCE	GFO	SUMO	SOWA	Cyc	BFO	UFO	BWW	UEMO	PDL	Chisholm	PROTON	PSI
[9]		×	×											
[9]			×		×									
[10]	×	×												
[11]		×	×	×	×	×								
[12]				×						×				
[13]		×	×					×	×					
[14]		×					×							
[15]		×							×					
[16]									×	×	×			
[17]									×			×		
[18]		×											×	

[19]	×	×		×										×

Table 1. Existing Comparison of Upper ontologies concepts

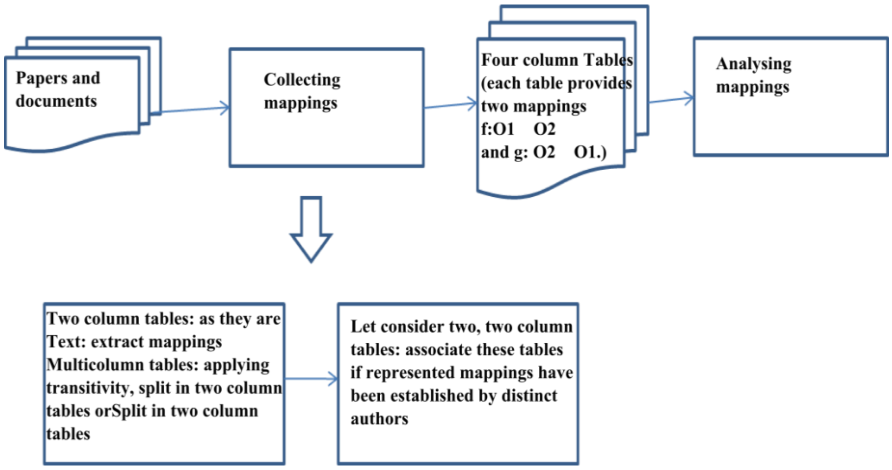

Fig. 2. Steps for finding compatibilities and incompatibilities in ontology mappings

3 Proposed method

We propose a method to find compatibilities and incompatibilies between ontology mappings (see **Fig. 2**). It has two main steps. (a) Collecting existing upper ontology mappings, (b) Analyzing collected mappings.

3.1 Collecting existing upper ontology mappings

In most of the cases found in the literature, relationships between mapped concepts are not qualified i.e. it remains unclear if the authors consider them as equivalence, subsumption, similarity and so on. Our proposal based on Galois connections does not require any information about the type of mapping such as equivalence, similarity and so on. In some cases, the authors do not specify any mapping for some concepts. In our proposal, we consider that the authors have tried to map all concepts, except if otherwise stated.

In our proposal, we have also taken care of the "format"' that the authors use for representing mappings. For mappings implicitly explained in the text, we have explicitly built a two column table for each couple of ontologies. For mappings directly provided as two column tables, we have just considered the same tables.

When dealing with a multicolumn table involving more than two ontologies, we have applied transitivity by assuming that, without specific assumptions provided by authors, the authors have used the same types of mapping for all ontologies.

To arrange the collected mappings, we have used several four column tables providing one mapping from some authors and an inverse mapping from some other authors. Extract of those tables is shown in **Fig. 3**. Each of these four column tables possibly provides distinct mappings between distinct ontologies, and can be used for the further analysis step.

DOLCE mapping by [15]	BWW mapping by [15]	DOLCE mapping by [13]	BWW mapping by [13]
Entity	Thing	Entity	Thing
		System	Endurant

Fig. 3. Arrangement of ontology mappings in four column table

3.2 Analyzing collected upper ontology mappings

The objective of this step is to verify if the couples of collected mappings respect Galois connection conditions. Compatible mappings have been further distinguished in weak compatible mappings and compatible mappings. The former rises whenever Galois connection conditions are trivially respected because some concepts are mapped to $\perp$.

Hereinafter, the reader can find in several situations, how compatibilities and incompatibilities have been established. According to definition 4, compatibilities and incompatibilities are stated per ontology artifacts. .

1. Trivial compatibility case

   $\alpha\,(\{\text{Category}\})_{GFO} = (\{\text{Abstract}\})_{Sowa}$

   $\gamma(\{\text{Abstract}\})_{Sowa}=(\{\text{Category}\})_{GFO}$

   $\alpha \circ \gamma\,(\{\text{Abstract}\})_{Sowa} =\alpha\,(\{\text{Category}\})_{GFO} = (\{\text{Abstract}\})_{Sowa}$

   $\gamma \circ \alpha(\{\text{Category}\})_{GFO} =\gamma(\{\text{Abstract}\})_{Sowa}=(\{\text{Category}\})_{GFO}$

The situation above corresponds to (one type of) Galois connection for specific concepts.

2. Weak compatibility case

   $\alpha(\{\text{MaterialStructure}\})_{GFO} = (\perp)_{DOLCE}$ $\gamma(\{\text{PhysicalEndurant}\})_{DOLCE} = (\{\text{MaterialStructure}\})_{GFO}$

   $\alpha \circ \gamma(\{\text{PhysicalEndurant}\})_{DOLCE} =\alpha(\{\text{MaterialStructure}\})_{GFO} = (\perp)_{DOLCE} \sqsubseteq (\text{PhysicalEndurant})_{DOLCE}$

   $\gamma \circ \alpha(\{\text{MaterialStructure}\})_{GFO} = \gamma(\perp)_{DOLCE} = (\perp)_{GFO} \sqsubseteq (\{\text{MaterialStructure}\})_{GFO}$

This means that the two mappings are compatible. It should be noted that the situation does not much change if instead of $\perp$, the ontology root, $\top$, would have been used. Indeed:

   $\alpha(\{\text{MaterialStructure}\})_{GFO} = (\top)_{DOLCE}$

   $\gamma(\{\text{MaterialStructure}\})_{GFO} = (\{\text{PhysicalEndurant}\})_{DOLCE}$

   $\alpha \circ \gamma\,(\{\text{PhysicalEndurant}\})_{DOLCE} =\alpha(\text{MaterialStructure}\})_{GFO} = (\top)_{DOLCE}$

   $\gamma \circ \alpha(\{\text{MaterialStructure}\})_{GFO} = \gamma\,(\top)_{DOLCE} = \top \sqsupseteq(\{\text{PhysicalEndurant}\})_{DOLCE}$

3. Compatibility case

A concept X in one ontology is mapped to some concept Y in other ontology, but in another mapping performed by some other author(s), X is mapped to Z which is subsumed by Y. i.e. $Z \subseteq Y$. For instance

$\alpha(\{\text{Process}\})_{GFO} = (\{\text{Stative}\})_{DOLCE}$
$\gamma(\{\text{Process}\})_{DOLCE}=(\{\text{Process}\})_{GFO}$
$\alpha \circ \gamma\ (\{\text{Process}\})_{DOLCE}= \alpha(\{\text{Process}\})_{GFO} = (\{\text{Stative}\})_{DOLCE}\subseteq(\{\text{Process}\})_{DOLCE}$
Stative is more general than Process, and Process is an immediate descendant of Stative.
$\gamma \circ \alpha(\{\text{Process}\})_{GFO} = \gamma(\{\text{Stative}\})_{DOLCE} = (\{\text{Process}\})_{GFO}$
which corresponds to a reverse ordering Galois connection.

4. Incompatibility case
A concept X in one ontology is mapped to some concept Y in another ontology, but X is mapped to Z, while Y and Z are not ordered.
$\alpha(\{\text{Region}\})_{GFO} = (\{\text{Space Region}\})_{DOLCE}$
$\gamma(\{\text{Spatial Location}\})_{DOLCE}=(\{\text{Region}\})_{GFO}$
$\alpha \circ \gamma\ (\{\text{Spatial Location}\})_{DOLCE}= \alpha(\text{Region})_{GFO} = (\{\text{Space Region}\})_{DOLCE}$
$\gamma \circ \alpha(\{\text{Region}\})_{GFO} = \gamma(\{\text{Space Region}\})_{DOLCE} = (\perp)_{GFO} = \perp$
Spatial Location and Space Region are subsumed by Physical Quality and Abstract Region respectively that are not ordered. This situation therefore does correspond to neither order reversing not order preserving Galois connection, rising in incompatibility.

4 Synthesis

The methodology presented in section 3 has been applied to available mappings (shown in table 1) whenever the two required mappings α and γ are established by distinct authors (however, it is possible to apply the methodology to mappings supplied by same authors). Compatibilities due to mapping to ⊥ are provided in italic (because they are “weak compatibilities” due to our interpretation of partial mappings). Table 2 is interpreted as a compatible ontology mapping couples and incompatible ontology mapping couples. A compatible mapping couple observes the properties of Galois connection and Incompatible mapping couples does not respect the properties of Galois connection. We have also applied our approach on GFO and Sowa's ontology; DOLCE and SUMO; DOLCE and WordNET; DOLCE and BWW.

Table 2. Compatibilities and Incompatibilities of DOLCE and GFO

Mappings couple α [9], γ [11]			
Compatibilities		**InCompatibilities**	
DOLCE	**GFO**	**DOLCE**	**GFO**
Particular	Individual	Event	{Change}, {Discrete Process}

Entity	*Entity*	{Spatial Location}, {Space Region}	Region
Perdurant	Occurrent		
{Quality}, {Physical Quality}	Property		
Stative	Process		
Material Structure	*Physical Endurant*		
State	*State*		
Time interval	*Chronoid*		
Endurant	*{Presential, Persistant}*		
Mappings couple α [13], γ [11]			
Compatibilities		**InCompatibilities**	
DOLCE	**GFO**	**DOLCE**	**GFO**
Particular	Individual		
Quality	*Quality*		
Entity	*Entity*		

5 Related Work

As said in the Introduction, several approaches to mappings between ontologies have been proposed in the literature. These approaches are not intended for any kind of ontology even if some rely on the specific formalization in which the ontology is represented. Hereinafter, we are going to review approaches that in our opinion are representative.

In [20] it is suggested to use Category theory approach for Ontology merging. In [3], an algebraic approach i.e. categorical approach is used to formally describe ontology merging, ontology alignment composition, union and intersection. They focus on defining suitable categorical representation of ontology alignments. However they define composition, union and intersection operation operations for ontology alignments without considering whether ontology alignments involve in these operations may generate inconsistencies.

In [4] it is suggested to use Argumentation to argue about acceptability of mappings issued by distinct agents. The disadvantage is that in addition to mappings there is the need to provide justification of such mappings, which in most cases are not available. Our approach does not consider justifications of mappings, so it can handle this kind of mappings. So However, our approach can be seen within the context of arguments. Indeed, if it is possible to say that if two functions α, γ are incompatible, couples (α, γ) or (γ, α) can be redefined as attacks. We do not define successful attack, but conflict free set can contain either α or γ, not both.

Researchers work on debugging and repairing of ontology alignment. [21] and [22] consider that ontologies are correct but if there is some inconsistency it is caused only by ontology mappings. [21] find the minimal conflict set that causes incoherent alignment, and then removes the correspondences causing inconsistencies by minimizing its impact. [22] uses the notion of minimal conflict sets and provides a mapping revision operator that modify alignment so that the result be consistent. Our incompatible mappings can be considered as minimal conflict set and can be first evaluated by these approaches for possible incoherence.

6 Conclusion

This paper has presented an approach of comparing mappings proposed by different authors. These mappings are usually stated for showing underlying similarities between upper ontologies, even when these ontologies have been designed by using fundamentally distinct design options. The methodology is based on Galois connections and on the definition of “mapping compatibility and incompatibility". We applied the methodology to available mappings (shown in Table 1) and in the paper we have provided a synthesis of the results concerning relevant couples of upper ontologies. These results show that all the mappings established between upper ontologies are weakly compatible or incompatible. We believe our work is useful in the context of upper ontologies. As upper ontologies are based on different design options, so they are very difficult to establish mappings between upper ontologies. So our work of classifying upper ontologies correspondence into compatible and incompatible mappings helps the user of upper ontologies when they used these ontologies in their applications.

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