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Ontology Merging: Compatible and Incompatible Ontology Mappings

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***Abstract*—Ontology mappings are used in data integration, query answering, and comparative analysis tasks of ontologies. Ontology mappings are often obtained by using a matching tool. Ontology merging is the creation of a new ontology from at least two source ontologies. In Ontology merging, establishing mappings between source ontologies is the primitive step. Ontology matching tools can be used for establishing mappings, but different matching tools often give dissimilar ontology mappings. Human intervention may not solve the problem because distinct perspectives and understandings also lead to different mappings. Attempts to face the problems have been studied in the literature. All these attempts focus on finding erroneous mappings and finding one consensual mapping. In this paper, we suggest that under some conditions, mappings can be combined to get benefits from each of them. Mappings satisfying those conditions are name compatible mappings; we argue that the conditions mentioned above are based on Galois connections. Opposed to compatible mappings, incompatible mappings cannot be combined because their combination results in erroneous mappings. We discussed our method in the context of ontology merging.**

Keywords—Ontology mapping; Galois connections; Compatible mappings; Incompatible mappings; Ontology merging

I. Introduction

Ontology mapping is defined as "map the entities of one ontology to at most one entity of another ontology" [1]. However, entities can be primitive or built by using the former. Mappings are usually abstract or concrete functions or relations between ontology artifacts (often concepts); mappings correspond to, precise or approximate, similarities, equality, subsumption [2]. More precisely, in simplest form, we can express mapping as a relation $\mathrm{r}:\langle\mathrm{a},\mathrm{b}\rangle$, where a and b are artifacts belonging to the two involved ontologies. This relation can be made concrete according to a logical or non-logical interpretation. Logical relations are subsumption ($\sqsubseteq, \sqsupseteq$), and the related equivalence, while non-logical relation can be similarity ($\approx$), general equivalence ($\equiv$) (such as the case of lexical equivalence), and substitution ($\phi(\mathrm{c_d})$). Finally, mappings involve central artifacts like concepts but also roles (properties) and other artifacts that need to be mapped.

Since many application fields use ontologies these days, the demand of matching system also increases. Also these matching systems are currently used in combination to produce better matching results. When there are more than one matching systems, they may give different matching results. When these matching results are combined and used with source ontologies, they may cause inconsistencies in ontologies. P. Shvaiko and J. Euzenat describe future challenges for ontology mapping and one of them is finding novel ways for combining ontology matching systems [3].

Instead of creating ontologies from scratch, existing ontologies can be reused and merged to create new ontologies. In this paper, we investigate the creation of ontologies by merging mapped ontologies. However, several mappings can have been established for performing the merging operation, by using matching tools or by hand.

We therefore propose a method that identifies which ontology mappings couples of two ontology mappings can be used together and which cannot. Combining several mappings is naturally useful for getting benefits of each mapping. A merged ontology O can be abstractly defined as $\mathrm{O} = \mathrm{merge}(\mathrm{O_A} \cup \mathrm{O_B} \cup \mathrm{M_{Ab}})$, where $\mathrm{O_A}$ is the first ontology and $\mathrm{O_B}$ is the second ontology, $\mathrm{M_{AB}}$ is the ontology mapping between $\mathrm{O_A}$and $\mathrm{O_B}$, and merge is the merge operation. In [4], we present a method for identifying incompatible ontology mappings, which are symmetric ($\mathrm{M_{AB}} = \mathrm{M_{BA}}$), in creating ontologies can cause unsatisfiability. In this paper we assume $\mathrm{M_{AB}}$ is supposed to be asymmetric i.e. $\mathrm{M_{AB}} \neq \mathrm{M_{BA}}$. Since it is not necessary that ontology mappings are symmetric [5], [6]. For instant, two ontologies describe the same domains with overlapping information, in this scenario, mappings are usually symmetric and they have a single universal interpretation domain. But when there are two ontologies describing a domain from different point of views, in this scenario, mappings are not symmetric and ontologies have their own interpretation domain.

If two distinct mappings $\mathrm{M_{AB}}$ and $\mathrm{M'_{BA}}$ are obtained by using different matching algorithms or matching tools or even manually by distinct experts, we define merged ontology as $\mathrm{O'} = \mathrm{merge}\{\mathrm{O_A} \cup \mathrm{O_B} \cup \mathrm{M_{AB}} \cup \mathrm{M'_{BA}}\}$. However, not all couples of mapping correspondences of $\mathrm{M_{AB}}$ and $\mathrm{M'_{BA}}$ can be used together. Some of them are deeply incompatible and are sources of further problems. For instance, if mappings are expressed as axioms in some Description Logics, saying that $\mathrm{M_{AB}}$ =A⊑B, $\mathrm{M'_{BA}}$=A⊑ C , being B and C disjoint in $\mathrm{O_B}$ leads to a problem if A is satisfiable in $\mathrm{O_A}$ and the merge operation simply adds those axioms to the union of these two ontologies

In this paper, we develop a method based on Galois connections for deciding when two mappings can be combined (used together) in the context of a merge operation. Galois connections are interesting because work on ordered structures (taxonomies are the basic structure for organizing, reasoning and analyzing ontologies). Therefore, Galois connections work independently if a mapping is concretely a logical relation

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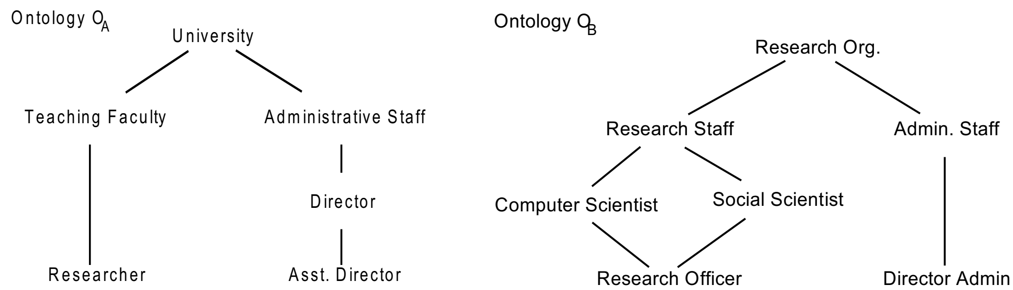

Fig. 1. Fragments of Ontology O_A and ontology O_B

(such as subsumption) or a non-logical relation (such as similarity). Galois connections work also if the ordered structure is just an order, a subsumption or a simple taxonomy. And finally, Galois connections may be used to map simple artifacts but also more complex artifacts (such as a set of axioms). It should be noted that in literature two mapping correspondences like $m_{AB} = A \sqsubseteq B$, $m'_{AB} = A \sqsubseteq C$ can be combined as union and the resulting mapping can be judged erroneous [7], [8], [9]. However, you can achieve the same result by using Galois connections which are however independently formulated and work well both if ontology is represented in logics but also if ontology is just a taxonomy or category. We therefore argue that Galois connections are the most adapted and theoretically sound and generic approach for evaluating when distinct mappings can be used together in the context of merge operation.

The paper is organized as follow. Section II provides a motivating merge scenario of this work. Related works are presented in Section III. Section IV describes the methodology to identify compatible (and incompatible) mappings being compatible mappings defined as two mappings that can be combined as a union. A discussion of contributions and future work concludes the paper in Section V.

II. A Motivating Scenario: Merging Ontologies

A new ontology can be created from other source ontologies by establishing mappings between source ontologies and then combining source ontologies and mappings.

Let consider two source ontologies O_A and O_B and their concepts as shown in **Erreur ! Source du renvoi introuvable.**. Links between ontology concepts are hierarchical relation. When there is no link between concepts, it means that these concepts are disjoint (or there is not order relation between them). Let also consider ontology mappings $M_{AB} =$ {(University, Research Org.), (Director, Director Admin), (Administrative Staff, Research Officer)}, and $M'_{BA} =$ {(Research Org., University), (Research Staff, Teaching Faculty), (Admin. Staff, Director), (Research Officer, Researcher), (Director Admin, Administrative Staff)}. Both M_{AB} and M'_{BA} can be used separately for creating a new ontology by using, for instance, categorical merge operation ([10], [11]). As M_{AB} and M'_{BA} are not same, users may want to get maximum advantage from both of them. There will be a risk that the combination operation may result in inconsistent ontology or there will be no resultant ontology.

Indeed, if mapping M_{AB} is rewritten in Distributed Description Logic [5] it may become (by using equivalence)

$O_A: \text{University} \xrightarrow{\equiv} O_B: \text{Research Org.}$
$O_A: \text{Director} \xrightarrow{\equiv} O_B: \text{Director Admin}$
$O_A: \text{Administrative Staff} \xrightarrow{\equiv} O_B: \text{Research Officer}$

and M'_{BA} as

$O_B: \text{Research Org.} \xrightarrow{\equiv} O_A: \text{University}$
$O_B: \text{Research Staff} \xrightarrow{\equiv} O_A: \text{Teaching Faculty}$
$O_B: \text{Admin. Staff} \xrightarrow{\equiv} O_A: \text{Director}$
$O_B: \text{Research Officer} \xrightarrow{\equiv} O_A: \text{Researcher}$
$O_B: \text{Director Admin} \xrightarrow{\equiv} O_A: \text{Administrative Staff}$

Using Category theory approach for ontology merging and mapping $M_{AB} \cup M'_{BA}$ results is undefined; using a Full-Merge approach [12] for ontology merging results in an incoherent ontology, and using a logical approach will also make the merged ontology incoherent. Therefore, in both cases, we can say that the two mappings cannot be combined. The underlying idea of Galois connections is to provide generic conditions, without referring to one specific theory (for instance, logics). We will explain these points in Section IV.

III. Related Work

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 [10] it is suggested to use Category theory approach for ontology merging. In [11], 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 (or mappings as called in this paper). However they define composition, union and intersection operation operations for ontology alignments without considering whether ontology alignments involved in these operations may be undefined.

In [13] 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 or difficult to be expressed, interpreted and used. However, our approach can be seen within the context of arguments. Indeed, if it is possible to say that if two mappings α, γ are incompatible (according to our definition Section IV),

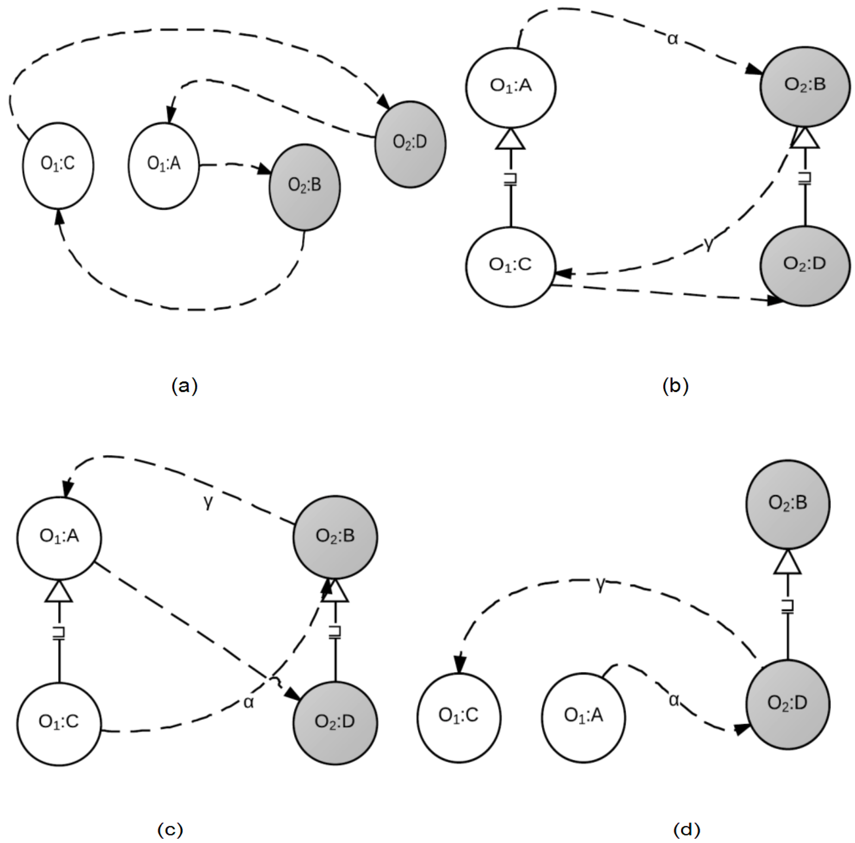

Fig. 2. Situations depending on the conditions required for Galois connections

couples (α, γ) or (γ, α) can be redefined as attacks. We however, define neither successful attack nor justifications because we do not want to achieve a consensus but to understand if two mappings can be combined.

There have also been several works on debugging and repairing of ontology alignment. An unsatisfiable concept in an ontology is defined as if it cannot be instantiated without causing inconsistency, and an incoherent ontology is defined as if an unsatisfiable concept occurs in it. A minimal conflict set in ontology mapping is defined as a set which causes unsatisfiability in the ontology and removing this set from the mappings removes unsatisfiability. [7], [8] consider that ontologies (to be merged) are correct and if there is some incoherence and/or inconsistency, it is caused only by ontology mappings. [7] finds the minimal conflict set that causes incoherent alignment, and then removes the correspondences causing unsatisfiability by minimizing its impact. [8] 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 a conflict set and should be evaluated by these approaches for possible incoherence.

[7], [8] focus on finding and repairing incoherent alignment , they consider that ontologies are more reliable than ontology mappings. In [9] authors find inconsistencies either caused by mappings are the intended ones and still there are logical inconsistencies, these logical inconsistencies are due to incompatible source ontologies. They propose a solution for repairing ontologies with the help of domain engineer.

In contrast to other approaches of debugging and/or repairing single ontology and/or single ontology alignment, our work is focused on more than one ontology mappings between two ontologies either generated by different tools or same tool using different algorithms.

IV. Compatibility and Incompatibility of Ontology Mappings

In this section, we present the Galois connection definitions and its importance for identifying and classifying ontology mappings that cannot use together in a single application. We then introduce the notion of compatibility and incompatibility of ontology mappings. We show that when mappings are incompatible it is not possible to create new merged ontology.

A. *Galois connections* (GC in the remainder)

In the literature, two definitions of Galois connection 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 $\alpha : A \to B$ and $\gamma : B \to A$, 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 as 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 it is:

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. Applicable to concrete relationships such as equality, subsumption, and abstract relationships such as similarity, substitution.

3. Applicable to concepts but also to relationships/properties *[14]* and to their taxonomies.

B. Ontology mapping compatibility and incompatibility

Except approximated mappings, precise mappings between ontologies are basically represented as functions or relation between ontology artifacts. Representing mappings as relations 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 $f \subseteq C_1 \times (C_2 \cup \{\perp\})$, $g \subseteq C_2 \times (C_1 \cup \{\perp\})$ (or even $g \subseteq C_1 \times (C_2 \cup \{\perp\})$), being ⊥ 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 connections, lets now define orders in power sets 2^{C_1} and 2^{C_2} in the same way as follows:

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

Two functions can then be easily defined as:

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

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 2(a) to 2(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 [15] 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. 2.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_1 as 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_2 being interpreted into O_1. Fig. 2.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 $\alpha'(\{C \dots\}) = \{\neg D, \dots\}$ (¬ is a negation connective). In practice, it is a negative interpretation saying what is not instead of what is. Fig. 2.c depicts one acceptable situation in which Galois connection conditions are not satisfied. In this case, α is an interpretation of O_1 into O_2, but O_2 cannot be interpreted in O_1 by γ therefore, f and g mappings (on which α and γ are built) are fundamentally distinct. Finally, Fig. 2.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 ontology 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 ontology mappings that are not compatible are said to be "incompatible".

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

Definition 4: Given ontology 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.

C. Compatible and incompatible ontology mappings in the context of ontology merging

We show how our proposed method can be used for finding compatible and incompatible ontology mappings. We apply this method to the example described in Section II, **Erreur ! Source du renvoi introuvable.**.

We will check the Galois connection condition between ontology mapping couples by using ontology structure for identifying compatibility and incompatibility. We use definition 4 for compatibilities and incompatibilities at artifact level. We present here one case of compatible and incompatible mappings from our example.

$\alpha(\{\text{Director}\}) = \{\text{Director Admin}\}$ according to M_{AB}

$\gamma(\{\text{Director Admin}\}) = \{\text{Administrative Staff}\}$ according to M'_{BA}

They form order preserving Galois connection as $\text{Director} \preccurlyeq \text{Administrative Staff}$ and $\text{Director Admin} \preccurlyeq \text{Director Admin}$.

While for mapping couple

$\alpha(\text{Administrative Staff}) = \text{Research Office}$ according to M_{AB}.

$\gamma(\text{Research Staff}) = \text{Teaching Faculty}$ according to M'_{BA}.

They neither form order preserving nor order reversing Galois connection as $\text{Research Officer} \preccurlyeq \text{Research Staff}$ and $\text{Administrative Staff} \not\preccurlyeq \text{Teaching Faculty}$ and $\text{Teaching Faculty} \not\preccurlyeq \text{Administrative Staff}$.

We will show the creation of new merged ontology with the help of mappings $M_{AB} \cup M'_{BA}$ by category theory approach, by Full-Merge operation [12], and by logical approach.

Categorical merge operation requires two properties to be fulfilled; a) The source ontologies must embed into merged ontology, b) merged ontology must not identify anything unnecessarily which are not present in the source ontologies. Categorical Pushout operation is shown in Fig. 3. These two properties are satisfied by the following two properties for categorical pushout operation.

(i) $e_A \circ p_A = e_B \circ p_B$.

(ii) For every other object O''_{AB} and morphisms $f_A: O_A \to O''_{AB}$, and $f_B: O_B \to O''_{B}$, with $f_A \circ p_A = f_B \circ p_B$ there is a unique morphism $m: O'_{AB} \to O''_{AB}$ such that $f_A = e_A \circ m$.and $f_B = e_B \circ m$.

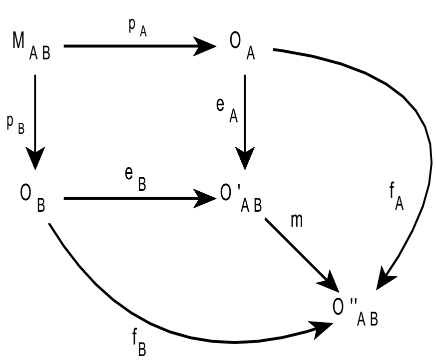

Fig. 3. Pushout operation for Categorical merge

Resulting ontology by using categorical merge operation with the help of pushout operation [10], [11] is shown in Fig. 4. Cross on Research Officer shows that due to this concept merge operation is not possible. Mapping correspondences in $M_{AB} \cup M'_{BA}$ are incompatible such as $\{m_{AB}$:(Administrative Staff, Research Officer), m'_{BA}:(Research Officer, Researcher)$\}$, as these ontology mapping couples do not establish Galois connection. This incompatible mapping is also verified from categorical merge operation, since artifact 'Research Officer' will violate the partial order relationship, present in the source ontology, and there is no pushout operation which will respect the partial order by using these mappings, so it is not possible to obtain new merged ontology by using categorical merge operation with the help of categorical pushout operation.

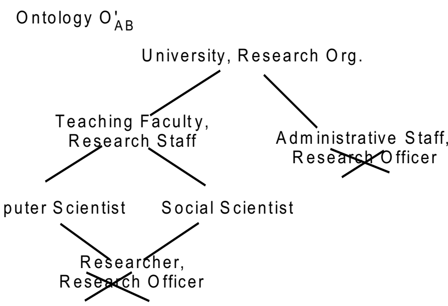

Fig. 4. Ontology obtained by merging O_A, O_B, and $M_{AB} \cup M'_{AB}$using Category Theory approach

We focus on Full Merge approach because it is the proper ontology merging according to the definition of merging by [1]. Source driven and Target driven merge solution falls in the category of ontology integration according to [1]. Fig. 5 shows the working of Full Merge approach [12]. Full-Merge approach produce merged ontology by taking union of input ontologies and combining equivalent concepts.

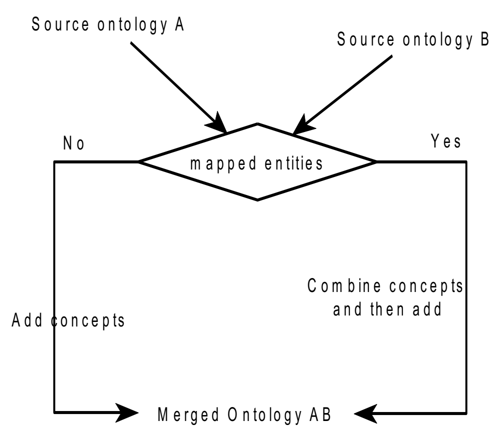

Fig. 5. Full Merge approach [12]

We create a new ontology merging, as shown in Fig. 6, by using Full-Merge operation [12]. We are using DDL logical equivalence as the equivalence required to apply full-merge. But we can see that ontology O'_{AB} obtained by using mapping $M_{AB} \cup M'_{AB}$ is incoherent. We present here only one incompatible case to show that resulting ontology is incoherent.

$\alpha(Administrative\ Staff\,) = \text{Research Officer}$, according to M_{AB}

$\gamma(\text{Research Officer}) = \text{Researcher}$, according to M'_{BA}. This mapping couple does not form GC, so the new ontology is incoherent as $\text{Researcher} \sqcap \text{Administrative Staff} \sqsubseteq \bot$ in ontology O_A but in resulting ontology $\text{Researcher} \equiv \text{Administrative Staff}$. Concepts marked with * in Fig. 6

represents that these concepts are redundant concepts and they should appear only one time in the merged ontology.

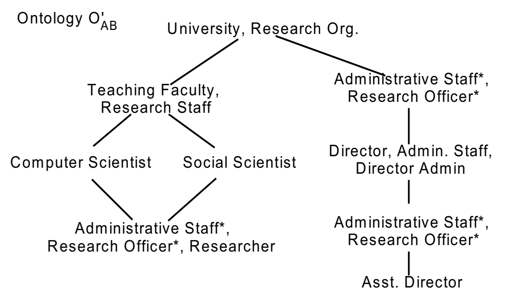

Fig. 6 Resulting Ontology obtained by merging O_A, O_B, and $M_{AB} \cup M'_{AB}$ using Full-Merge [12] approach

In logical approach, the new merged ontology is not created, $O_1 \cup O_2 \cup M_{AB} \cup M'_{BA}$ is considered as merged ontology and it provides the same inferences which merged ontology provides. The main property of mappings is that it should not contradict the axioms of original ontologies.

We can see that there are unsatisfiable concepts in $O_1 \cup O_2 \cup M_{AB} \cup M_{BA}$., such as in O_A has axiom $\text{Researcher} \sqcap \text{Administrative Staff} \sqsubseteq \perp$, while in $O_1 \cup O_2 \cup M_{AB} \cup M_{BA}$, we can derive

$$O_A\text{: Administrative Staff} \xrightarrow{\equiv} O_B\text{: Research Officer, and}$$

$$O_B\text{: Research Officer} \xrightarrow{\equiv} O_A\text{: Researcher}$$

and we can infer from above

$$O_A\text{: Researcher} \equiv O_A\text{: Administrative Staff}$$

So by above inference, O_A: Researcher and O_A: Administrative Staff become unsatisfiable concepts, and creating any instances of these concepts create inconsistency and we can derive $\top \sqsubseteq \perp$, so $O_1 \cup O_2 \cup M_{AB} \cup M_{BA}$ is incoherent. such as $\{m_{AB}$:(Administrative Staff, Research Officer), m'_{BA}: (Research Officer, Researcher)$\}$, as these ontology mapping couples do not establish Galois connection.

We have shown only the case when correspondences in one ontology mappings are incompatible. It should be noted that when GC conditions are not satisfied if the mapping is reinterpreted in some theories (such as Category, logics) where a merge operation is denied, the resulting ontologies may be incoherent/inconsistent or not existing. We argue that the GC conditions are common to all theories defining merging operation.

V. DISCUSSION

The method we have proposed is based on Galois connections and on the definition of "mapping compatibility and incompatibility". In Section IV, we have applied the method to the example introduced in Section II; The main contributions conveyed by the proposed method are (i) identifying incompatible ontology mappings, which give a-priori information to the user whenever merge operation by using couple of mappings is not possible, (ii) applicability to ontologies that may expressed by different formalisms, (iii) applicability to domain ontologies but also to upper ontologies which are mostly hierarchically organized. The case of upper ontology is interesting as recognized in [16] where some criteria to identify fundamentally distinct mappings are defined. Future Work will focus on developing a tool to automate the method. Automation will made possible an extensive analysis of mappings samples recognized in practical works, literatures, concerning both domain and upper ontologies.

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