Towards Principles for Ontology Integration

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Abstract. Resolving conflicts based on ambiguities in the public vocabulary is one of the challenges in semantic integration. Though different suggestions for resolving (ambiguity) conflicts with semantic integration operators exist, there is still a need for clear formalizations of adequacy criteria for the operators. In this article, adequacy criteria for semantic integration similar to rationality postulates of classical belief revision but adjusted to the semantic integration scenario are formalized. The criteria are intended to capture integration settings in which the integration candidates are well developed ontologies with a shared public vocabulary. In such cases, both ontologies have to be preserved in some form in the integration result and have to be recoverable from the integration result. Additionally, the integration result has to be consistent and provide connections between the integrated ontologies. The criteria are applied by evaluating a small collection of integration operators that solve conflicts deriving from ambiguities in the public vocabulary.

Keywords. Ontology integration, belief revision, semantic mapping, reinterpretation

1. Introduction

An ontology for some domain is an important means for knowledge sharing among communication partners. It provides formal descriptions of relevant concepts, relations and individuals of the domain. Additionally, in most cases an ontology is represented in some formalism for which tractable reasoning mechanisms exist [1]. Though an ontology is intended to enable communication, in practice there may be many possibly heterogeneous ontologies. Heterogeneities between ontologies can lead to conflicts (mismatches) prohibiting the seamless interoperability between the communication partners. Semantic integration is concerned with the problem of making information from different knowledge sources interoperable by integrating them—taking into account the possible heterogeneity of the knowledge sources.

There are different types of mismatches. One of the mismatches on the ontology level are ambiguities. Ambiguous terms occur frequently in natural languages but can be found in formal representations of ontologies, too. E.g., in one bibliographical ontology *Article* may denote all documents that are published in a journal. In another bibliograph-

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ical ontology *Article* may denote the wider concept of all documents that were published in a journal, proceedings or in a collection ([2], p. 4). In this article, the focus is on conflicts that can be explained by ambiguities in the public vocabulary. Here, a symbol in the public vocabulary is termed ambiguous if it belongs to different terminologies in the sense that it has different specifications in different ontologies.

In the semantic-integration literature, different strategies for yielding interoperability of heterogeneous ontologies are suggested. Though in most cases it is reasonable to claim that the strategies yield adequate integration results, there is still a need to formally explicate the underlying principles or adequacy criteria. Formal principles for semantic integration provide a means for specifying the properties of a given strategy and form the basis for comparing different integration strategies. Depending on the integration setting, different adequacy criteria may result. In the intended setting of this article, two ontologies are integrated. The ontologies are meant to be used in the same domain, hence it is assumed that the ontologies are kindred. Furthermore, the ontologies are well-tried and well developed and especially have no internal conflicts. Both ontologies have a shared public vocabulary which can lead to ambiguity conflicts between them. Due to the similarity condition an adequate integration result for this setting has to provide connections between the ontologies. As the initial ontologies are free from conflicts also the outcome should be free from conflicts. Moreover, as the ontologies are well developed, an adequate integration result should preserve both ontologies in some form.

I formalize the adequacy criteria in the line of postulates which have proved of value in classical belief revision [3]. The postulates axiomatize classes of binary integration operators suitable for the intended integration setting by explicating the properties for the integration operators. As the whole set of postulates formalizing the adequacy criteria is inconsistent, I define (two) classes of integration operators based on uniform reinterpretation that fulfill (two different) subsets of the postulates and thereby show that the subsets of the whole set of postulates are consistent. Additionally, I use the postulates to analyze a selection of integration operators proposed in the literature and compare them with the uniform-reinterpretation operators.

2. The Role of Semantic Mappings in Semantic Integration

Research on (ontology-based) semantic integration is centered on the formal representation of semantic mappings, the reasoning with semantic mappings, and the discovery of semantic mappings [1].

One representation format for semantic mappings is given by *bridging axioms* [2]. In [2] ontologies are represented in different name spaces so that the vocabularies of the ontologies are disjoint. Bridging axioms are defined as sentences in some superset of the ontologies' vocabularies that relate corresponding terms of the ontologies. The ontologies and bridging axioms together constitute a theory which allow to apply a uniform reasoning procedure. In operationalizing the principles for adequate integration I use bridging axioms to map corresponding concepts and roles of different ontologies.

Another representation format for semantic mappings, called *views*, is used in the ontology integration systems framework [4]. Views are functions that map concepts and roles of a global ontology to corresponding concepts and roles of local ontologies. In the formulation of the preservation criterion for semantic integration, I use substitutions that relate concepts and roles of the original ontology and its preserved version in the integration result. The substitutions are comparable with views.

A third kind of semantic mapping implicitly contained in the framework of Qi et al. [5], which is outlined in Section 5, are weakening functions. These functions map axioms to other (weaker) axioms rather than symbols to other symbols.

The last representation format for semantic mappings to be mentioned here is embedded in the general framework of distributed systems (DS) [6] or the more specific framework of distributed description logics [7]. A distributed system consists of local ontologies and ontology alignments, which are defined as the whole set of semantic mappings between two ontologies. Different from bridging axioms, the semantic mappings between the local ontologies are not axioms in a global ontology but additional components relating corresponding concepts and roles in the local ontologies. Therefore, a DS needs a reasoning procedure different from the reasoning procedures of the local ontologies. In [6] and [7] the semantic basis for the reasoning procedures is established by defining special distributed semantics for distributed systems which also explicate the semantic role of the semantic mappings. In the case of distributed semantics, it does not matter whether the local ontologies share a vocabulary or not. There is no distinction between a public vocabulary for communication between the ontologies and a private vocabulary. Hence, ambiguities in a public vocabulary cannot occur.

There are different methods to establish semantic mappings. One method is based on shared upper ontologies like DOLCE [8]. Upper ontologies are meant to provide a common understanding of general terms which can be used by lower level domain-specific ontologies extending the upper ontologies. If ontologies are built on a common upper ontology, the number of ambiguity conflicts may be reduced in comparison with the case where no common upper ontology exists. But still ambiguities can occur between terms not explicated in the upper ontology. Therefore, additional mechanisms are necessary for resolving ambiguity conflicts.

Another method for establishing mappings uses heuristics, [9], [10], [11] or machine learning techniques [12]. The heuristics are guided by, e.g., natural-language descriptions, concept descriptions or structural or logical properties of the ontologies. Adequate semantic integration demands an integration result which displays clear connections to the original ontologies and relates (parts of) the integrated ontologies. Hence, whatever kind of heuristics is used, it has to facilitate the construction of semantic mappings that realize these connections and relations.

3. Adequacy Criteria for Ontology Integration Operators

A formal representation of adequacy criteria for integration strategies in some integration setting has the advantage of specifying exactly the properties an integration strategy has or should have. Additionally, different strategies for the same integration setting can be compared with regard to the formal adequacy criteria. Postulates as used in the area of belief revision have proved useful for specifying properties of revision strategies. Grounded in the pioneering work of Alchourrón, Gärdenfors and Makinson [3] (AGM), belief revision was designed to capture rational change of beliefs by proposing postulates that have to be fulfilled by contraction resp. revision functions. The basic AGM postulates in the adapted form described in [5] are the starting point for the following postulates for semantic integration but have to be adapted and extended for the intended integration setting.

In the integration setting for which the following postulates are intended, an agent holding an ontology O_1 wants to integrate a kindred ontology O_2 received from a different agent into his ontology O_1. Both ontologies are defined over a common public vocabulary $\mathcal{V}$ of non-logical symbols, formally expressed with $\mathcal{V}(O_1), \mathcal{V}(O_2) \subseteq \mathcal{V}$. As there may be symbols in $\mathcal{V}$ that have different specifications in O_1 and O_2 ambiguity conflicts in the public vocabulary can occur and have to be resolved. That an ontology is free from conflicts can formally be described by the concept of consistency. The set $Mod(O)$ denotes the set of *models* of O, i.e., the set of interpretations that make all sentences of O true. An ontology is *consistent* (free from conflicts) iff it has a model. The outcome of the integration is denoted by $O_1 \circ O_2$ where $\circ$ is a binary integration operator. As both ontologies, O_1 and O_2, are assumed to be well developed, there is a strong need to preserve both ontologies in $O_1 \circ O_2$.

The preservation of the ontologies can be formalized with the help of *substitutions*. Substitutions are functions mapping non-logical symbols to terms of the same type. As I intend to use substitutions for the preservation of ontologies in integration settings with ambiguity conflicts, I define the subclass of Ambiguity Resolution Substitutions. Let $\mathcal{V}_p$ be a (public) vocabulary and let $\mathcal{V}'$ be a disjoint (private) vocabulary, $\mathcal{V}_p \cap \mathcal{V}' = \emptyset$. The set of *Ambiguity Resolution Substitutions* $ARS(\mathcal{V}_p, \mathcal{V}')$ (or just ARS) is the set of injective substitutions that map a non-logical symbol in $\mathcal{V}_p$ either to itself or to a new non-logical symbol (of the same type) in $\mathcal{V}'$. E.g., $\sigma \in ARS(\mathcal{V}_p, \mathcal{V}')$ could map a concept symbol $K_1 \in \mathcal{V}_p$ to itself $K_1 = \sigma(K_1)$ or to another concept symbol $K_1' = \sigma(K_1) \in \mathcal{V}'$. The set of symbols $s \in \mathcal{V}_p$ for which $\sigma(s) \neq s$ is called the *support* of σ. Substitutions are extended to sentences and sets of sentences in the usual way. The ontology $\sigma(O)$ or alternatively $O\sigma$ is called a *substitution variant* of O.

The following postulates are intended to describe operators that are guaranteed to resolve terminology-dependent inconsistencies between two ontologies without loosing (parts of) the ontologies. An operator $\circ$ *fulfills* a postulate if and only if the postulate is true for all input ontologies O_1 and O_2.

As ontologies provide a conceptualization of a domain, the mere syntactic difference in the representation of an ontology should not lead to semantic changes of the integration strategies referring to the ontology. This criterion is expressed by the *extensionality postulates* (O1.1) and (O1.2). Additionally, the criterion is underlying the other postulates as they refer to the models of the ontologies and not to their syntactic structure.

(O1.1) If $\mathcal{V}(O_1) = \mathcal{V}(O_1')$ and $Mod(O_1) = Mod(O_1')$, then $Mod(O_1 \circ O_2) = Mod(O_1' \circ O_2)$

(O1.2) If $\mathcal{V}(O_2) = \mathcal{V}(O_2')$ and $Mod(O_2) = Mod(O_2')$, then $Mod(O_1 \circ O_2) = Mod(O_1 \circ O_2')$

If two ontologies are compatible, there is no reason to assume that their terminologies are different. In this case (like for AGM-revision-operators) an adequate way to integrate the ontologies is to form their union.

(O2) If $O_1 \cup O_2$ is consistent, then $Mod(O_1 \circ O_2) = Mod(O_1 \cup O_2)$

Terminology-dependent conflicts between the ontologies occur because they share a common public vocabulary. A resolution of the conflicts should preserve as much of the terminologies and of the shared vocabulary as possible. Otherwise the integrated ontology $O_1 \circ O_2$ would not support communication (integration) based on the interface vocabulary. The *monotony postulate* (O3.1) says that all sentences derivable in O_1 are derivable in the resulting ontology and thus expresses a strict form of preservation of O_1. The *success postulate* (O3.2) expresses a strict form of preservation of O_2 in the sense that all sentences derivable in O_2 are still derivable after the integration.

(O3.1) $Mod(O_1 \circ O_2) \subseteq Mod(O_1)$
(O3.2) $Mod(O_1 \circ O_2) \subseteq Mod(O_2)$

Since the integration result $O_1 \circ O_2$ should be consistent if possible (see Postulate (O6) below) the criteria formalized by (O3.1) and (O3.2) cannot be fulfilled by an integration operator at the same time unless $O_1 \cup O_2$ is consistent. Hence (O3.1) and (O3.2) are not principles for all semantic integration operators but suggest the definition of two alternative types of operators (see Section 4). In the case of conflicts, the integration process has to abandon parts of O_1 or O_2.

As the ontologies are well developed and well-tried, it is desirable to preserve both ontologies in some form. One way to preserve an ontology is to transfer it to a substitution variant in a different name space. The *preservation postulates* (O4.1) and (O4.2) demand the existence of substitutions such that the substitution variants of O_1 resp. O_2 are contained in the resulting ontology.

(O4.1) There is a substitution σ_1 with: $Mod(O_1 \circ O_2) \subseteq Mod(O_1\sigma_1)$
(O4.2) There is a substitution σ_2 with: $Mod(O_1 \circ O_2) \subseteq Mod(O_2\sigma_2)$

Postulate (O4.1) can be considered as a generalization of the monotony postulate (O3.1) (letting σ_1 be the identity function) and (O4.2) as a generalization of the success postulate (O3.1). Although there are no operators that fulfill (O3.1) and (O3.2) in the presence of (O6), it is possible to define operators that fulfill (O3.1) and (O4.2) or (O3.2) and (O4.1) in the presence of (O6). The feature of preserving both ontologies in the integration result is the essential point at which integration operators differ from classical belief-revision and update operators. Belief-revision and update operators fulfill success, i.e., integrate O_2 as a whole, but only at cost of loosing parts of the ontology O_1. The preservation postulates demonstrate that the goal of semantic integration is different from the goals of belief revision and belief update. Belief revision aims at solving conflicts due to false information. Belief update aims at solving conflicts due to outdated information. Semantic integration (based on reinterpretation) aims at solving conflicts due to ambiguous use of terms.

The following postulates represent additional generalizations of (O3.1) and (O3.2). Postulates (O5.1) and (O5.2) require the existence of substitutions such that the old ontologies O_1 and O_2 can be recovered by applying the substitution to the integration result. These postulates are termed *substitution recovery postulates*.

(O5.1) There is a substitution σ_1 with: $Mod((O_1 \circ O_2)\sigma_1) \subseteq Mod(O_1)$
(O5.2) There is a substitution σ_2 with: $Mod((O_1 \circ O_2)\sigma_2) \subseteq Mod(O_2)$

If an operator fulfills both preservation postulates, (O4.1) and (O4.2), then for any ontologies O_1 and O_2 that can be integrated there are substitutions σ_1, σ_2 such that $Mod(O_1 \circ O_2) \subseteq Mod(O_1\sigma_1) \cap Mod(O_2\sigma_2) = Mod(O_1\sigma_1 \cup O_2\sigma_2)$. Consequently, the existence of σ_1, σ_2 such that $O_1\sigma_1 \cup O_2\sigma_2$ is consistent is a necessary condition for the consistency of the integration result. This condition expresses the fact that there are no vocabulary-independent conflicts between the ontologies. Two ontologies O_1, O_2 are called *reinterpretation compatible* iff substitutions σ_1, σ_2 exist such that $O_1\sigma_1 \cup O_2\sigma_2$ is consistent. The *weakened consistency postulate* (O6) makes reinterpretation compatibility of O_1 and O_2 a sufficient criterion for the consistency of the result.

(O6) If O_1 and O_2 are reinterpretation compatible, then $O_1 \circ O_2$ is consistent

If two ontologies are reinterpretation compatible, then each ontology is consistent. As in the central cases of semantic integration the integrated ontologies are consistent, there is no need for postulates that specify the operator for inconsistent O_1 or inconsistent O_2.

Belief-revision and belief-update operators fulfill stronger versions of (O6). Belief-revision operators guarantee consistency of the result if O_2 is consistent. Belief-update operators guarantee consistency if O_1 and O_2 are consistent [13].

Postulates (O1.1), (O2), (O3.2) correspond to the AGM postulates named extensionality, vacuity and success [3]. Postulate (O6) is a weakening of the consistency postulate of AGM. Postulates (O4.1), (O4.2) and (O5.2), (O5.2) are additional postulates capturing the ideas of preservation and substitution recovery.

4. Uniform Reinterpretation Operators

The aim of this section is to operationalize the postulates discussed in Section 3. I will show that there exist (two) subsets of the postulates that are fulfilled by (two) different reinterpretation operators, respectively.

The postulates of Section 3 do not presuppose an exact specification of the representation format for ontologies. For this and the following section I assume that an ontology is represented as a finite set of sentences in a description logical (DL) language.[2] But it is equally possible to represent the ontologies with predicate logics as the definitions of the operators below do not depend on the use of DLs. In a DL language, the set of non-logical symbols, denoted by $\mathcal{V}$ or indexed variants, consists of constants, denoted by a, b, c and indexed variants, concept symbols, denoted by K and indexed variants, and role symbols, denoted by R and indexed variants. $\mathcal{V}(O)$ is the set of all non-logical symbols occurring in O. $\mathcal{V}_c$ is the set of all constants, $\mathcal{V}_{CR}$ the set of all concept and role symbols occurring in $\mathcal{V}$. Concept descriptions are built using concept constructors and are denoted by the meta-variables C, D and indexed variants. The set of concept constructors used in this article contains concept negation $\neg$, concept conjunction $\sqcap$, and concept disjunction $\sqcup$.

The sentences of an ontology can be classified as *TBox axioms*, which express terminological knowledge, and the *ABox axioms*, which express world knowledge. TBox axioms are of the form $C \sqsubseteq D$ (All C are D), so called GCIs (General Concept Inclusions), or of the form $R_1 \sqsubseteq R_2$ for role symbols R_1, R_2, so called role inclusion axioms. The ABox axioms are of the forms $C(a)$ (a is a C) or $R(a, b)$ (a is R-related to b).

The core idea for the definition of reinterpretation operators is developed in [15]. The operators of [15] get as first argument an ontology and as second argument a *literal*, i.e., a sentence of the form $K(a)$ or $\neg K(a)$ for a concept symbol K.

[2] For details regarding the definitions and the syntax of DLs see [14].

In this article, I extend the operators of [15] to ontology-integration operators allowing ontologies as second arguments. Therefore, not only one symbol but a set S of symbols has to be considered for disambiguation. Additionally, not only concept symbols but also role symbols or constants are considered as candidates for disambiguation.

In order to develop the definition of the uniform-reinterpretation operators, let O_1 and O_2 be two ontologies with a common vocabulary $\mathcal{V} \supseteq \mathcal{V}(O_1 \cup O_2)$. Let $\mathcal{V}_{12} = \mathcal{V}(O_1) \cap \mathcal{V}(O_2)$ denote the shared set of non-logical symbols. Further, let $\mathcal{V}'$ be a new vocabulary of private symbols, $\mathcal{V}' \cap \mathcal{V} = \emptyset$. Further, let $S \subseteq \mathcal{V}_{12}$ be a subset of the set of common non-logical symbols and let $\rho_S \in ARS(\mathcal{V}, \mathcal{V}')$ be a substitution with support S.

If $O_1 \cup O_2$ is inconsistent and O_1 and O_2 are reinterpretation compatible, the inconsistency can be explained by ambiguous symbols $S \subseteq \mathcal{V}_{12}$ in the shared vocabulary. The inconsistency can be resolved by decoupling the ontologies O_1 and O_2 with respect to S, either yielding $O_1 \cup O_2\rho_S$ or $O_2 \cup O_1\rho_S$. In the first decoupling, the terminology of O_1 is preserved. For O_2, the first decoupling results in a shift in the meaning of the common symbols in S, they are reinterpreted. In the second decoupling, the terminology of O_2 is preserved and a shift in the meaning of the common symbols in S for O_1 results. As the substitution ρ_S is applied to all occurrences of symbols in O_1 resp. O_2 that stem from S the reinterpretation operators are termed *uniform*. A successful decoupling should select a symbol set $S \subseteq \mathcal{V}_{12}$ such that the decoupled ontologies $O_1 \cup O_2\rho_S$ resp. $O_2 \cup O_1\rho_S$ are consistent. The set $MRS(O_1, O_2)$ of Minimal Reinterpretation Symbols

$$\begin{aligned} MRS(O_1, O_2) = \{S \subseteq \mathcal{V}_{12} \mid\ & Mod(O_1 \cup O_2\rho_S) \neq \emptyset \text{ and for all } S_1 \subset S: \\ & Mod(O_1 \cup O_2\rho_{S_1}) = \emptyset\} \end{aligned} \tag{1}$$

describes all inclusion-minimal symbol sets that lead to a consistent union of decoupled ontologies. A direct consequence of the definition is that $MRS(O_1, O_2) = MRS(O_2, O_1)$ and that $MRS(O_1, O_2) = \{\emptyset\}$ iff $O_1 \cup O_2$ is consistent. The set $MRS(O_1, O_2)$ is empty iff O_1 and O_2 are not reinterpretation compatible. In this case the reinterpretation operators cannot resolve the inconsistency between O_1 and O_2. (Compare Postulate (O6)). Choosing inclusion-minimal symbol sets realizes the idea of reinterpreting only those symbols that are involved in a conflict. As there are no formal criteria which of the sets in $MRS(O_1, O_2)$ have to be chosen, the operator definition will be parameterized by a selection function γ. A *selection function* γ is a function that maps a set to a subset, such that $\gamma(\emptyset) = \emptyset$ and for all sets $M \neq \emptyset$: $\emptyset \neq \gamma(M) \subseteq M$. So, if $MRS(O_1, O_2)$ is not empty, a selection function γ picks a non-empty subset of all inclusion-minimal symbol sets S that result in a consistent decoupling of O_1 and O_2. The union of these sets results in $S^* = \bigcup \gamma(MRS(O_1, O_2))$ which is the set of all disambiguated symbols in the reinterpretation process.

As O_1 and O_2 are assumed to be kindred ontologies, the reinterpretation operators relate the different readings for the disambiguated symbols in S by special terminological axioms which function as bridging axioms. The axioms relate a concept resp. role symbol s to a new private concept resp. role symbol $\sigma(s)$. For concept and role symbols $s \in S$ the set $\{s \sqsubseteq \sigma(s) \mid s \in S_{CR}\}$ contains a lower bound for $\sigma(s)$ and $\{\sigma(s) \sqsubseteq s \mid s \in S_{CR}\}$ contains an upper bound for $\sigma(s)$. The set $A(S, \sigma)$ of all possible bounds additionally contains identities for constants in S.

$$A(S, \sigma) = \{s \sqsubseteq \sigma(s), \sigma(s) \sqsubseteq s \mid s \in S_{CR}\} \cup \{s = \sigma(s) \mid s \in S_c\} \tag{2}$$

Given an ontology O, a set of symbols S and a substitution σ with support S, the set $MB(S, \sigma, O)$ (set of Maximal sets of Bounds) contains all inclusion-maximal sets of bounds that can be consistently added to O. To describe the set $MB(S, \sigma, O)$ formally, I use a construction similar to the remainder-sets construction in partial-meet revision [16]. For sets of sentences A, B let $A \oplus B$ denote the set of inclusion maximal subsets of A that are compatible with B.

$$A \oplus B = \{X \subseteq A \mid Mod(X \cup B) \neq \emptyset \text{ and for all } Y \subseteq A : \text{If } X \subset Y, \text{ then } Mod(Y \cup B) = \emptyset\} \tag{3}$$

So $MB(S, \sigma, O)$ can be defined by

$$MB(S, \sigma, O) = A(S, \sigma) \oplus O \tag{4}$$

A second selection function γ_2 is used to select a subset of the maximal sets of bounds. Similar to the approach in partial meet revision, the set of bounds to be added is the intersection of inclusion maximal sets selected by γ_2.

Using the notation above, type-1 and type-2 operators can be defined.

Definition 1 *Let γ_1, γ_2 be selection functions and let $\overline{\gamma} = (\gamma_1, \gamma_2)$. Let $\mathcal{V}, \mathcal{V}'$ be disjoint vocabularies, and let O_1, O_2 be ontologies with $\mathcal{V}(O_1 \cup O_2) \subseteq \mathcal{V}$. Let $S^* = \bigcup \gamma_1(MRS(O_1, O_2))$ and let $\rho_{S^*} \in ARS(\mathcal{V}, \mathcal{V}')$ be a substitution with support S^*. Then the* weak uniform-reinterpretation operators of type-1 *respectively* of type-2 based on $\overline{\gamma}$ and ρ_{S^*} *are defined by:*

$$O_1 \otimes_1^{\overline{\gamma}, \rho_{S^*}} O_2 = O_1 \cup O_2\rho_{S^*} \cup \bigcap \gamma_2\Big(MB(S^*, \rho_{S^*}, O_1 \cup O_2\rho_{S^*})\Big) \tag{5}$$

$$O_1 \otimes_2^{\overline{\gamma}, \rho_{S^*}} O_2 = O_2 \cup O_1\rho_{S^*} \cup \bigcap \gamma_2\Big(MB(S^*, \rho_{S^*}, O_2 \cup O_1\rho_{S^*})\Big) \tag{6}$$

A direct consequence of the definition is the interdefinability of $\otimes_1^{\overline{\gamma}, \rho_{S^*}}$ and $\otimes_2^{\overline{\gamma}, \rho_{S^*}}$, i.e., $O_1 \otimes_1^{\overline{\gamma}, \rho_{S^*}} O_2 = O_2 \otimes_2^{\overline{\gamma}, \rho_{S^*}} O_1$. The main observation concerns the fulfillment of the postulates.

Observation 1 *Let O_1, O_2 be ontologies, let γ_1, γ_2 be selection functions, let $S^* = \bigcup \gamma_1(MRS(O_1, O_2))$ and let ρ_{S^*} be a substitution with support S^*. Then*

1. $\otimes_1^{\overline{\gamma}, \rho_{S^*}}$ *fulfills (O1.1), (O1.2), (O2), (O3.1), (O4.1), (O4.2), (O5.1), (O5.2) and (O6) but does not fulfill (O3.2) (success).*
2. $\otimes_2^{\overline{\gamma}, \rho_{S^*}}$ *fulfills (O1.1), (O1.2), (O2), (O3.2), (O4.1), (O4.2), (O5.1), (O5.2) and (O6) but does not fulfill (O3.1) (monotony).*

The effect of the operators can be illustrated with a small example on bibliographic ontologies. Let two ontologies be given by

$$O_1 = \{Article \sqsubseteq \forall publ.Journ, Journ \sqsubseteq \neg Proceed, publ(med01, procFOIS08), Proceed(procFOIS08)\} \tag{7}$$

$$O_2 = \{Article(med01)\} \tag{8}$$

Assume that the holder of O_1 integrates O_2 with a weak type-2 operator, i.e., decides to preserve O_2 in its original form. According to O_1, all articles are published in journals, and journals are different from proceedings. The ABox-part says that $med01$ is published in the proceedings of FOIS08. The TBox of O_2 is empty. The ABox-part says that $med01$ is an article. These two ontologies are not compatible. The set of minimal reinterpretation symbols $MRS(O_2, O_1)$ consists of the sets $\{med01\}$ and $\{Article\}$, i.e., reinterpreting the constant $med01$ or the concept symbol $Article$ of O_1 is sufficient to get decoupled consistent ontologies.

Deciding to reinterpret $med01$—thereby introducing a new symbol $med01' = \rho_{\{med01\}}(med01)$ for the constant $med01$ of O_1—means that $med01$ is thought to be ambiguous. This choice can be formalized by a selection function γ_1 with $\gamma_1^1(MRS(O_2, O_1)) = \{\{med01\}\}$. The choice fits to situations where $med01$ is used in O_1 to denote a publication in the proceedings of FOIS08 and $med01$ is used in O_2 to denote the follow-up article published in a journal. The weak operators do not relate constants, so for all bound selection functions γ_2^1 the integration result is

$$O_1 \otimes_2^{(\gamma_1^1,\gamma_2^1),\rho_{\{med01\}}} O_2 = O_{1[med01/med01']} \cup O_2 \tag{9}$$

The choice to reinterpret $Article$ fits to situations in which both ontologies speak about the same publication in the proceedings of FOIS2008 but in which $Article$ in O_2 is used in a broader sense than $Article$ according to O_1. This can be formalized by a selection function γ_1^2 with $\gamma_1^2(MRS(O_2, O_1)) = \{\{Article\}\}$. The unique maximal consistent set of bridging axioms is $\{Article' \sqsubseteq Article\}$, so all selection functions γ_2^2 fulfill $\gamma_2^2(\{\{Article' \sqsubseteq Article\}\}) = \{Article' \sqsubseteq Article\}$. The integration result is

$$O_1 \otimes_2^{(\gamma_1^2,\gamma_2^2),\rho_{\{Article\}}} O_2 = O_{1[Article/Article']} \cup \{Article' \sqsubseteq Article\} \cup O_2 \tag{10}$$

By broadening the set of potential bounds $A(S, \sigma)$ it is possible to define stronger versions of the operators. For the following comparison with [5] it is sufficient to adapt the strong operators of [15], which are defined only for literals as second arguments. In adapting the definitions of [15], I use *nominals*, i.e., concept descriptions $\{a\}$ whose extension consists exactly of the individual denoted by a. As only the type-2 operators will be compared with the operators of [5], the definitions of the type-1 operators are skipped. A *concept literal* is either a concept symbol K or a negated concept symbol $\neg K$. The meta-variable $\hat{K}$ is used for concept literals.

Definition 2 *Let O be an ontology over the vocabulary $\mathcal{V} \cup \mathcal{V}'$ with $\mathcal{V} \cap \mathcal{V}' = \emptyset$, $K \in \mathcal{V}$ be a concept symbol and $\hat{K}$ be a concept literal with $\mathcal{V}(\hat{K}) = \{K\}$. Let σ be a substitution with support $\{K\}$. The* strong uniform-reinterpretation operators of type 2 $\odot_2^C$ *that reinterpret the concept symbol are defined for literals by*

$$O \odot_2^C \hat{K}(a) = \begin{cases} O \cup \{\hat{K}(a)\} & \text{if } O \cup \{\hat{K}(a)\} \text{ is consistent,} \\ O\sigma \cup \{\hat{K}(a), \sigma(\hat{K}) \sqsubseteq \hat{K}, \hat{K} \sqsubseteq \sigma(\hat{K}) \sqcup \{a\}\} & \text{else} \end{cases} \tag{11}$$

The additional axiom $\hat{K} \sqsubseteq \sigma(\hat{K}) \sqcup \{a\}$ contributes to the strength of the operator. It says that a denotes the only individual that is $\hat{K}$ but not $\sigma(\hat{K})$. For an analysis of weak and strong operators for triggering literals and iterated applications confer [15].

5. Other Approaches to Integration

In the following, the postulates given in Section 3 are used to compare the belief-revision-oriented frameworks of Delgrande and Schaub [17] and Qi, Liu and Bell [5] and the semantic-integration-oriented framework of Goeb, Reiss, Schiemann and Schreiber [18] with the uniform-reinterpretation approach.

5.1. Private and Public Vocabularies in Belief Revision

The idea of using different vocabularies (private vs. public) in the integration process is not new to the belief-revision literature. Delgrande and Schaub [17] use this idea to define two belief-revision operators $\dot{+}, \dot{+}_c$. The belief-revision operators $\dot{+}$ (skeptical revision) and $\dot{+}_c$ (choice-revision) take as input two propositional knowledge bases over a public vocabulary $\mathcal{V}$ of proposition variables. Inconsistencies between the knowledge bases O_1, O_2 are resolved by completely decoupling O_1 and O_2. All proposition variables p in O_1 are substituted by new symbols $p' \in \mathcal{V}'$ where $\mathcal{V}'$ is a private vocabulary with $\mathcal{V}' \cap \mathcal{V} = \emptyset$. The decoupling yields the knowledge base $O_1\rho_{\mathcal{V}} \cup O_2$. The decoupled knowledge bases are related by adding maximal sets of biimplications $p \leftrightarrow p'$ between the old symbols p and the new symbols p' that are consistent with the $O_1\rho_{\mathcal{V}} \cup O_2$. In the case of $\dot{+}$ the intersection of all maximal sets of biimplications are added to the decoupled knowledge bases, in the case of $\dot{+}_c$ one maximal set selected by a selection function c is added to the decoupled knowledge bases. The result of the addition is closed with respect to a classical inference operator and intersected with the set of sentences containing only proposition variables from the public vocabulary.

The operators $\dot{+}, \dot{+}_c$ and the uniform-reinterpretation operators have many properties in common. For example, both classes of operators introduce a new private vocabulary in order to resolve conflicts. Moreover, the biimplications used in the definitions of $\dot{+}, \dot{+}_c$ can be considered as bridging axioms. But there are some essential differences. Delgrande and Schaub define $\dot{+}, \dot{+}_c$ for propositional knowledge bases which are not suitable for representing ontologies. Furthermore, [17] only considers biimplications $p \leftrightarrow p'$ and not implications $p \rightarrow p'$ which would directly correspond to subsumption relations $C \sqsubseteq C'$ between concept symbols used in the definitions of the reinterpretation operators. Lastly, the revision outcomes with respect to $\dot{+}$ or $\dot{+}_c$ are knowledge bases over the public vocabulary $\mathcal{V}$. The new symbols are introduced only as auxiliary variables for the revision procedure and do not occur in the revision result. Therefore the revision operators $\dot{+}, \dot{+}_c$ do not fulfill the preservation or substitution-recovery postulates for the first argument. But, $\dot{+}, \dot{+}_c$ fulfill extensionality in both arguments, vacuity, success and weakened consistency.

Observation 2 *The revision operators $\dot{+}, \dot{+}_c$ defined in [17] fulfill (O1.1), (O1.2), (O2), (O3.2), (O4.2), (O5.2) and (O6) but they do not fulfill (O4.1), (O5.1).*

5.2. Non-uniform Reinterpretation

Goeb et al. [18] describe an algorithm for the integration of a sender's ontology O_2 into a receiver's ontology O_1. Their framework tackles ontology integration in a very similar way as the uniform-reinterpretation operators. The main distinction relies in the nonuniformity of the operators described in [18]. For the following, let TB_i denote the TBox, AB_i the ABox of O_i, $i \in \{1, 2\}$. The outcome of the integration is denoted by $O^{\circledast}$.

The algorithm has two main steps. In the first step, the ontologies are completely decoupled with respect to the common vocabulary $\mathcal{V}(O_1) \cap \mathcal{V}(O_2)$. This is similar to the decoupling in the case of the operators $+, +_C$ in [17]. For every concept and role symbol s (but not constants) two new symbols are introduced, a symbol $\sigma_1(s)$ for the receiver's symbol s, and a symbol $\sigma_2(s)$ for the sender's symbol s. The symbols are related in so called *triangles*, i.e., subsumption relations of the form $\sigma_1(s) \sqsubseteq s$ and $\sigma_2(s) \sqsubseteq s$ for $\sigma_1, \sigma_2 \in ARS$. After the reinterpretation, s denotes a super-concept of the receiver's and sender's s-concepts. The super-concept s neither belongs to the terminology of the receiver nor does it belong to the terminology of the sender. As there may be symbols with respect to which no decoupling is necessary for yielding consistency some symbols are re-translated into their original form. The decoupling is reduced to a inclusion-minimal set $S \in MRS(O_1, O_2)$ of symbols that cannot be consistently re-translated.

In the second step of the algorithm, additional consistent re-translations are applied. But this time the re-translations do not have to be uniform, i.e., different occurrences of the same symbol may be treated differently with respect to the decision to re-translate or not. The outcome of the re-translation can formally be described by applying substitutions to different parts of the ontologies. Let

$$\Sigma_1^S = \{\sigma : S \longrightarrow \sigma_1(S) \cup S \mid \text{For all } s \in S : \sigma(s) = s \text{ or } \sigma(s) = \sigma_1(s)\} \tag{12}$$

denote the set of substitutions that possibly substitute less symbols with new ones than σ_1. Similarly Σ_2^S is defined. Using this notation, the following representation of the ontology $O^{\circledast}$ results. There are

- symbol sets $S_1, S_2 \subseteq S$;
- substitutions $\tau_{AB_1} \in \Sigma_1^{S_1}$ and $\tau_{AB_2} \in \Sigma_2^{S_2}$, such that $\tau_{AB_1}(s) \notin S$ for all $s \in S_1$ and $\tau_{AB_2}(s) \notin S$ for all $s \in S_2$;
- partitions of the TBoxes $TB_1 = \biguplus_{1 \leq i \leq k} TB_{1i}$ and $TB_2 = \biguplus_{1 \leq i \leq l} TB_{2i}$;
- substitutions $\tau_{11}, \ldots, \tau_{1k} \in \Sigma_1^{S_1}$ and $\tau_{2i}, \ldots, \tau_{2l} \in \Sigma_2^{S_2}$

such that

$$\begin{aligned} O^{\circledast} = & \bigcup_{1 \leq i \leq k} T_{1i}\tau_{1i} \cup \bigcup_{1 \leq i \leq l} T_{2i}\tau_{2i} \cup (AB_1)\tau_{AB_1} \cup (AB_2)\tau_{AB_2} \cup \\ & \{\tau_{AB_1}(s) \sqsubseteq s \mid s \in S_1\} \cup \{\tau_{AB_2}(s) \sqsubseteq s \mid s \in S_2\} \end{aligned} \tag{13}$$

The representation of $O^{\circledast}$ in Eq. (13) says that for all $\alpha \in O_1$ a substitution variant (for a substitution in $\Sigma_1^{S_1}$) occurs in $O^{\circledast}$. Accordingly, for all $\alpha \in O_2$ there exists a substitution variant in $O^{\circledast}$. The substitutions τ_{AB_1}, τ_{AB_2} are uniform semantic mappings for the receiver's resp. the sender's ABox. The sets $\{\tau_{AB_1}(s) \sqsubseteq s \mid s \in S_1\}$ and $\{\tau_{AB_2}(s) \sqsubseteq s \mid s \in S_2\}$ can be considered as bridging axioms. The fact that $(AB_1)\tau_{AB_1} \subseteq O^{\circledast}$ means that a substitution variant of the receiver's ABox as a whole is contained in $O^{\circledast}$. Accordingly, $(AB_2)\tau_{AB_2} \subseteq O^{\circledast}$ means that a substitution variant of the sender's ABox as a whole is contained in $O^{\circledast}$. But note that in general it cannot be guaranteed that substitution variants of the receiver's or sender's ontology are contained in $O^{\circledast}$. Consequently, the operators of [18] do not fulfill the preservation postulates (O4.1), (O4.2) or recovery postulates (O5.1), (O5.2). Hence, also (O3.1), (O3.2) are not fulfilled.

Due to the non-uniform reinterpretations realized by the different substitutions τ_{1i} and τ_{2j} neither the left (O1.1) nor the right (O1.2) extensionality postulates are fulfilled. Thus, only postulates (O2) and (O6) are fulfilled by the operators of [18].

Observation 3 *The integration operator described in [18] fulfills (O2) and (O6) but it does not fulfill (O1.1), (O1.2), (O3.2), (O3.1), (O4.2), (O4.1), (O5.2) and (O5.1).*

5.3. Ontology Revision Based on Weakening Axioms

The framework of Qi, Liu and Bell [5] provides binary belief-revision operators for the revision of an ontology with another ontology.[3] The ontologies are represented by multisets of description logical axioms. The operators do not introduce new symbols. Rather, axioms α of the first ontology are mapped (weakened) to axioms $(\alpha)_w$ such that $Mod(\alpha) \subseteq Mod((\alpha)_w)$. The weakenings can be considered as semantic mappings that map axioms of one ontology to other axioms. Some axioms are mapped onto themselves, other axioms are mapped to weaker axioms. As Qi, Liu and Bell consider two different types of weakening, also two binary operators are defined, a revision operator $\circ_w$ and a refined revision operator $\circ_{rw}$. For a comparison with the uniform-reinterpretation operators, I focus on $\circ_w$.[4]

The weakening $(\cdot)_w$ on which $\circ_w$ relies is based on the idea of exception lists. GCIs α of the form $C \sqsubseteq D$ are weakened to GCIs $(\alpha)_w$ of the form $C \sqcap \neg\{a_1\} \sqcap \ldots, \sqcap\neg\{a_n\} \sqsubseteq D$, which means that all Cs, except for the individuals $a_1, \ldots, a_n$, are Ds. An ABox-axiom is mapped to itself or radically weakened to the tautology $\top$, which amounts to deleting it. A degree function $d(\cdot)$ counts the number of exceptions. The degree of $C \sqcap \neg\{a_1\}, \ldots, \sqcap\neg\{a_n\} \sqsubseteq D$ is n, the degree of an ABox-axiom α is 0 if it is mapped to itself and 1 if it is mapped to the tautology $\top$. O' is a weakened ontology of O_1 with respect to O_2, formally $O' \in Weak^w_{O_2}(O_1)$, iff $O' \cup O_2$ is consistent and there exists a bijection f from O_1 to O' such that for all $\alpha \in O_1$ the axiom $f(\alpha)$ is a weakening of α. The degree $d(O')$ of O' is the sum of the degrees of its axioms. The operator $\circ_w$ is defined by

$$\begin{aligned} O_1 \circ_w O_2 = \{O_2 \cup O_i \mid O_i \in Weak^w_{O_2}(O_1) &\text{ and there exists no} \\ O_j \in Weak^w_{O_2}(O_1) &\text{ such that } d(O_j) < d(O_i)\} \end{aligned} \tag{14}$$

The revision result contains unions of O_2 with d-minimal weakenings of O_1. The set is interpreted as the disjunction of the ontologies it contains.

The main common idea of the approach presented in [5] and the approach of uniform reinterpretation is that of weakening. E.g., let $O_1 = \{K_1 \sqsubseteq K_2, K_1(a)\}$ and $O_2 = \{\neg K_2(a)\}$, then $\{K_1 \sqcap \neg\{a\} \sqsubseteq K_2, K_1(a), \neg K_2(a)\} \in O_1 \circ_w O_2$. The axiom $K_1 \sqsubseteq K_2$ is weakened to $K_1 \sqcap \neg\{a\} \sqsubseteq K_2$.

The reinterpretation operator $\odot^C_2$ applied to the same ontologies results in $O_1 \odot^C_2 \neg K_2(a) = \{K_1(a), K_1 \sqsubseteq K_2', \neg K_2' \sqsubseteq \neg K_2, \neg K_2 \sqsubseteq \neg K_2' \sqcup \{a\}\}$. (Here $\rho_{\{K_2\}}(K_2)$ is abbreviated by K_2'). As in the case of $\circ_w$ the weakened axiom $K_1 \sqsubseteq K_2 \sqcup \{a\}$ follows from $O_1 \odot^C_2 \neg K_2(a)$. The perspective on weakening in [5] is a little bit different from the perspective on weakening for the uniform-reinterpretation operators. Because $\circ_w$ weakens axioms

[3] Qi et al. do not use the term *ontology* but only description logical knowledge bases.

[4] The weakening underlying the operator $\circ_{rw}$ allows non-trivial weakenings of axioms of the form $(\forall R.C)(a)$

while the reinterpretation operators weaken atomic concepts. For the example above one sees that weakening $K_1 \sqsubseteq K_2$ to $K_1 \sqcap \neg\{a\} \sqsubseteq K_2$ realizes an implicit weakening of the concept K_2 to $K_2 \sqcup \{a\}$ as $K_1 \sqcap \neg\{a\} \sqsubseteq K_2$ is logically equivalent to $K_1 \sqsubseteq K_2 \sqcup \neg\{a\}$. But it is not always possible to interpret the weakening of axioms as the weakening of some atomic concept. The implicit weakening of a complex concept description D in $C \sqcap \neg\{a\} \sqsubseteq D$ only concerns D as a whole, and not the weakening of an atomic concept.

As the consistency resolution in $\circ_w$ is guided by degree minimality and is not terminology-oriented like the uniform-reinterpretation operators, axiom-oriented consistency resolution is possible. Hence, different occurrences of the same concept symbol can be handled differently in resolving the inconsistencies. For the example, note that $\{\top, K_1 \sqsubseteq K_2, \neg K_2(a)\} \in O_1 \circ_w O_2$, i.e., here, the axiom $K_1(a) \in O_1$ is weakened to $\top$ while the axiom $K_1 \sqsubseteq K_2 \in O_1$ which also contains K_1 is not weakened. Consequently, the operator $\circ_w$ does not fulfill the postulates (O4.1) and (O5.1) which demand the preservation and recovery of O_1. The axiom-oriented resolution of conflicts is also responsible for non-extensionality in the left argument of $\circ_w$. The following observation lists the postulates (not) fulfilled by $\circ_w$.

Observation 4 *The operator $\circ_w$ of weakening-based revision fulfills (O1.2), (O2), (O3.2), (O4.1), (O5.1) and (O6) but does not fulfill (O1.1), (O4.1) and (O5.1).*

As Qi, Liu and Bell show, the weak revision operators fulfill a stronger version of (O6). They can guarantee consistency of the integration result if O_2 is consistent. In particular, if O_1 is inconsistent, the operator $\circ_w$ resolves the inconsistencies independently of O_2.

6. Conclusion

Formal adequacy criteria for the integration of ontologies allow a precise specification of the properties of integration strategies and provide a basis for a comparison of different strategies for the same integration setting. The criteria are formalized in the article by postulates in the same line as discussed in the area of belief revision [3]. Though the classical AGM postulates are the core of the integration postulates, the set of additional preservation and substitution-recovery postulates (O4.1), (O4.2), (O5.1) and (O5.2), which accommodate for the setting's presumption that both ontologies are well-tried cannot be fulfilled by classical belief-revision and belief-update functions.

The uniform-reinterpretation operators of type 1 and type 2 show that there are two maximal subsets of the postulates that can be fulfilled by two different classes of operators each of which guarantees a consistent integration result and the preservation and recovery of both ontologies as a whole. Both operators resolve possible conflicts between the ontologies by mapping one of the ontologies in a different name space. The type-1 operators preserve the first ontology in its original form, the second ontology is translated to a substitution variant by using an ambiguity resolution substitution. In the case of type-2 operators the second ontology is preserved and the first ontology is translated to a substitution variant. The substitutions used in the operators function as semantic mappings between the public terminology used for communication and the private terminology resulting from the integration process. Semantic mappings relating the concepts and roles of the different ontologies are represented by inclusion axioms which have the role of bridging axioms.

The revision operators of [17] and the weakening-based belief-revision operators defined in [5] can guarantee a consistent integration result (O6) in which O_2 is preserved in its original form (O3.2). But only parts of O_1 are preserved in the result, i.e., (O4.1), (O5.1) are not fulfilled. The operators defined in [18] can guarantee a consistent integration result (O6). But, as the ambiguous terms are not reinterpreted uniformly neither of the ontologies is preserved as a whole in the integration result, i.e., (O3.1), (O3.2), (O4.1), (O4.2), (O5.1) and (O5.2) are not fulfilled.

References

[1] N. F. Noy, "Semantic integration: A survey of ontology-based approaches.," *SIGMOD Record*, vol. 33, no. 4, pp. 65–70, 2004.

[2] D. Dou, D. V. McDermott, and P. Qi, "Ontology translation by ontology merging and automated reasoning," in *Proceedings of EKAW2002 Workshop on Ontologies for Multi-Agent Systems*, pp. 3–18, 2002.

[3] C. Alchourrón, P. Gärdenfors, and D. Makinson, "On the logic of theory change: partial meet contraction and revision functions.," *Journal of Symbolic Logic*, vol. 50, pp. 510–530, 1985.

[4] D. Calvanese, G. D. Giacomo, and M. Lenzerini, "Ontology of integration and integration of ontologies.," in *Description Logics*, vol. 49 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2001.

[5] G. Qi, W. Liu, and D. Bell, "A revision-based approach to handling inconsistency in description logics," in *Proceedings of the 11th International workshop on Non-Monotonic Reasoning (NMR06)*, 2006.

[6] A. Zimmermann and J. Euzenat, "Three Semantics for Distributed Systems and their Relations with Alignment Composition," in *The Semantic Web - ISWC 2006, 5th International Semantic Web Conference, Proceedings* (I. F. Cruz, S. Decker, D. Allemang, C. Preist, D. Schwabe, P. Mika, M. Uschold, and L. Aroyo, eds.), pp. 16–29, Springer, 2006.

[7] A. Borgida and L. Serafini, "Distributed description logics: Assimilating information from peer sources," *Journal on Data Semantics*, vol. 1, pp. 153–184, 2003.

[8] A. Gangemi, N. Guarino, C. Masolo, and A. Oltramari, "Sweetening WORDNET with DOLCE," *AI Magazine*, vol. 24, no. 3, pp. 13–24, 2003.

[9] N. Noy and M. Musen, "The prompt suite: Interactive tools for ontology merging and mapping," *International Journal of Human-Computer Studies*, vol. 59, no. 6, pp. 983–1024, 2003.

[10] J. Euzenat and P. Valtchev, "Similarity-based ontology alignment in OWL-Lite," in *ECAI* (R. L. de Mántaras and L. Saitta, eds.), pp. 333–337, IOS Press, 2004.

[11] P. Bouquet, L. Serafini, and S. Zanobini, "Semantic coordination: A new approach and an application," in *The Semantic Web - ISWC 2003, Second International Semantic Web Conference, Proceedings* (D. Fensel, K. P. Sycara, and J. Mylopoulos, eds.), pp. 130–145, Springer, 2003.

[12] A. Doan, J. Madhavan, R. Dhamankar, P. Domingos, and A. Halevy, "Learning to match ontologies on the semantic web," *The VLDB Journal*, vol. 12, no. 4, pp. 303–319, 2003.

[13] H. Katsuno and A. Mendelzon, "On the difference between updating a knowledge base and revising it," in *KR'91: Principles of Knowledge Representation and Reasoning* (J. F. Allen, R. Fikes, and E. Sandewall, eds.), pp. 387–394, San Mateo, California: Morgan Kaufmann, 1991.

[14] F. Baader, "Description logic terminology," in *The Description Logic Handbook* (F. Baader, D. Calvanese, D. McGuinness, D. Nardi, and P. F. Patel-Schneider, eds.), pp. 495–505, Cambridge UP, 2002.

[15] Ö. L. Özçep and C. Eschenbach, "On the conservativity and stability of ontology revision operators based on reinterpretation," in Beierle and Kern-Isberner [19], pp. 84–99.

[16] C. Alchourrón and Makinson, "Hierarchies of regulations and their logic," in *New Studies in Deontic Logic*, pp. 125–148, D. Reidel Publishing, 1981.

[17] J. P. Delgrande and T. Schaub, "A consistency-based approach for belief change," *Artificial Intelligence*, vol. 151, no. 1-2, pp. 1–41, 2003.

[18] M. Goeb, P. Reiss, B. Schiemann, and U. Schreiber, "Dynamic T-box-handling in agent-agent-communication," in Beierle and G.Kern-Isberner [19], pp. 100–117.

[19] C. Beierle and G. Kern-Isberner, eds., *Dynamics of Knowledge and Belief. Proceedings of the Workshop at the 30th Annual German Conference on Artificial Intelligence, KI-2007*, Fernuniversität Hagen, 2007.