Minimality Postulates for Semantic Integration

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Abstract. Though for a long time the set of classical belief revision belief postulates of Alchourrón, Gärdenfors and Makinson (AGM) was thought to incorporate a principle of minimality, according to which the outcome of revising a knowledge base (KB) by new information had to be minimally different from the original KB, it was realised that one had to add additional postulates, called relevance postulates, in order to exclude forgetful revision. In this paper, we investigate two minimality postulates for a particular semantic integration scenario in which conflicts are caused by ambiguous use of symbols: A relevance postulate which says that only conflict relevant information is allowed to be eliminated and a generalised inclusion postulate which limits the creativity of the operators. Both postulates exploit the (satisfiably) equivalent representation of a first order logic KB by its prime implicates, which are its most logical atoms. As an example for a revision based operator in a semantic integration scenario, the definition of reinterpretation operators is recapitulated and it is shown that these fulfil both postulates.

1 INTRODUCTION

Not long after the seminal papers of Alchourrón, Gärdenfors and Makinson (AGM) [1, 2] it was realised that belief-revision techniques could be fruitfully applied for ontology based semantic integration [23], in particular for different types of ontology change such as ontology evolution, ontology alignment, ontology merge, ontology debugging etc. [13]. Most of the work exploiting belief revision for ontology change [14, 21, 12, 29, 28, 27] follows the general two-way approach of classical belief revision of, on the one hand, defining axiomatic specifications in the form of postulates and, on the other hand, constructing operators that fulfil these postulates.

Postulates provide means to declaratively describe the properties that an (revision, merge, integration etc.) operator to be built in some application context or scenario should fulfil. Moreover, postulates allow for the comparison of different operators. In this paper, we will look at postulates that are intended to specify a minimal change of a knowledge base (or more concretely an ontology) and show that their is a class of operators (reinterpretation operators) fulfilling them.

The intended integration scenario of this paper for which the minimality postulates are going to be developed can be described as follows. A receiver agent holds an ontology which is formally described by a knowledge base (KB) in some expressive formal language like first order logic (FOL) or a fragment of it (like description logic). In particular, a KB is a finite set of sentences in FOL (or a fragment of it). He receives information from another agent, who owns a possibly but only minimally different ontology, and he wants to integrate the information into his ontology.

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It is assumed that both the sender's KB and the receiver's KB are well developed ontologies over the same application domain (e.g., ontologies for an online library system in universities); further it is assumed that the terms used in the ontologies either denote the same individuals, concepts and relations or are strongly related. Nonetheless, there may be terms that are used in different (related) ways in between the sender's and the receiver's KB (ambiguous use of terms). Here we constrain the ambiguous use to terms that denote concepts or relations but not individuals. Think, e.g., of two ontologies for an online library system where the receiver uses the term $Article$ in order to denote publications either in proceedings or journals while the sender uses $Article$ in a narrower sense to stand only for publications in journals. The receiver is assumed to give priority to the sender's meanings of the symbols and so the integration result will contain the trigger (this is similar to classical belief revision and different from non-prioritised belief revision [17]) and trigger a change of the receiver's ontology to conserve consistency. But, as the ontology of the receiver is assumed to be well developed the receiver is interested in changing his ontology only minimally, i.e., he wants to delete sentences of his KB and add additional sentences to it only as much as needed.

In belief revision the theme of minimality is mainly dealt with within the context of relevance postulates [16, 26] which specify that only those sentences of the receiver's KB that are relevant for conflicts with the trigger are allowed to be eliminated. But also inclusion postulates [18] can be seen as contributions to a minimal-change specification as they limit the operators's "creativity" by prescribing an upper bound to the result. In this paper, we start from these postulates for classical belief revision, argue why they are not proper minimality specifications for the intended integration scenario and formulate radically adapted versions that exploit the fine grained structure of ontologies by the notion of prime implicates. This adaptation is needed for aligning the symbol-oriented conflict diagnosis of the integration scenario (ambiguous use of symbols causes the conflict) with the fact that conflicts show themselves on the level of sentences.

The work of this paper continues previous work on integration operators for the intended integration scenario [11, 24]. We show that the reinterpretation operators, which exploit the idea of reinterpreting symbol's of the receiver's ontology and relating them with bridging axioms [10], fulfil the adapted relevance and inclusion postulate.

The paper is structured as follows. After this introduction we gather the logical preliminaries in Sect. 2. Section 3 describes relevance and inclusion postulates for belief revision operators that are associated with minimal change and argues why they are not adequate specifications for the intended integration scenario. Sections 4 and 5 describe new relevance and inclusion postulates that fit to the intended integration scenario. The last section before the conclusion, Sect. 6, defines a class of integration operators that fulfil the new postulates. An extended version of this paper containing full proofs can be found under the URL http://dl.dropbox.com/u/65078815/oezcep12relevanceExt.pdf or http://www.sts.tu-harburg.de/people/oezcep/papers/papers.html.

2 LOGICAL PRELIMINARIES

A first order logic (FOL) vocabulary $\mathcal{V}$ consists of constants, predicate symbols and function symbols. For a FOL formula or set of formulas X let $\mathcal{V}(X)$ be the set of non-logical symbols occurring in X. A *literal* is an atomic or a negated atomic formula. The notion of a FOL *structure or interpretation* $\mathcal{I} = (\Delta^{\mathcal{I}}, \cdot^{\mathcal{I}}) \in \mathrm{Int}(\mathcal{V})$ over a vocabulary $\mathcal{V}$ is defined as usual; $\Delta^{\mathcal{I}}$ is the *domain* and $\cdot^{\mathcal{I}}$ is the *denotation* function; the truth of a formula α in $\mathcal{I}$, denoted $\mathcal{I} \models \alpha$ or equivalently $\alpha^{\mathcal{I}} = \mathrm{true}$, is defined in the well known Tarskian style. Let P be a unary predicate symbol, $D \subseteq \Delta^{\mathcal{I}}$ and $\mathcal{I}$ an interpretation. The interpretation $\mathcal{I}_{[P \mapsto D]}$ is called a P-variant of $\mathcal{I}$; it has the same denotations as $\mathcal{I}$ for all non-logical symbols except P, which is interpreted by D. For other non-logical symbols the variant is defined similarly. FOL formulas without free variables are called *sentences*. The set of sentences containing only non-logical symbols in the vocabulary $\mathcal{V}$ are denoted $\mathrm{Sent}(\mathcal{V})$. The set of sentences in $\mathrm{Sent}(\mathcal{V})$ following from a set of sentences X (over a perhaps larger vocabulary) is denoted by $\mathrm{Cn}^{\mathcal{V}}(X)$. If two sets of FOL sentences X_1, X_2 are logically equivalent, we write $X_1 \equiv X_2$.

A non-logical symbol $s \in \mathcal{V}$ *properly occurs in a sentence* $\alpha \in \mathrm{Sent}(\mathcal{V})$ iff there are FOL interpretations $\mathcal{I}_1, \mathcal{I}_2 \in \mathrm{Int}(\mathcal{V})$, s.t.: $\mathcal{I}_1$ and $\mathcal{I}_2$ differ only in the denotation of s and $\alpha^{\mathcal{I}_1} \neq \alpha^{\mathcal{I}_2}$. Let $P \in \mathcal{V}$ be an n-ary predicate symbol in $\mathcal{V}$. It occurs *syntactically positive (negative)* in an FOL formula iff it occurs in the scope of an even (uneven) number of negations—assuming that only the propositional truth functions $\wedge, \vee, \neg$ are used. For $P \in \mathcal{V}(\alpha)$ we say that *P occurs semantically positive in sentence α*, $posOcc(P, \alpha)$ for short, iff: For all interpretations $\mathcal{I} = (\Delta^{\mathcal{I}}, \cdot^{\mathcal{I}})$ and for subsets $D_1, D_2 \subseteq (\Delta^{\mathcal{I}})^n$ of the n-ary cartesian product of $\Delta^{\mathcal{I}}$ one has: If $D_1 \subseteq D_2$ and $\mathcal{I}_{[P \mapsto D_1]} \models \alpha$, then also $\mathcal{I}_{[P \mapsto D_2]} \models \alpha$. *$P$ occurs semantically negative in sentence α*, $negOcc(P, \alpha)$ for short, iff $posOcc(P, \neg\alpha)$. P occurs *mixed in* α, $mixOcc(P, \alpha)$ for short, iff it properly occurs in α but neither $posOcc(P, \alpha)$ nor $negOcc(P, \alpha)$. We write $posOccOrNot(P, \alpha)$ (resp. $negOccOrNot(P, \alpha)$) iff $posOcc(P, \alpha)$ (resp. $negOcc(P, \alpha)$) or P does not occur syntactically in α.

The reinterpretation operators described in Sect. 6 are based on the concept of *dual remainder sets* [8, 29, 24], which is similar to the concept of remainder sets [2] used in the classical paper of AGM [1] for the construction of partial-meet revision functions. Let $B \top \alpha$, *the dual remainder sets modulo* α, denote the set of inclusion maximal subsets X of B that are consistent with α, i.e., $X \in B \top \alpha$ iff $X \subseteq B$, $X \cup \{\alpha\}$ is consistent and for all $\bar{X} \subseteq B$ with $X \subset \bar{X}$ the set $\bar{X} \cup \{\alpha\}$ is not consistent. The notion of dual remainders is extended to arbitrary KBs B_1 as second argument by defining $B \top B_1$ as $B \top \bigwedge B_1$.

3 MINIMALITY IN BELIEF REVISION

In his paper on two dogmas of belief revision, Hans Rott [30] pointed out the long standing belief (dogma) that classical belief revision à la Alchourrón, Gärdenfors and Makinson (AGM) [1] obeys a principal of minimality, according to which a KB is allowed to be revised only minimally in the light of new information. The AGM postulates do not constrain the revision result in the main interesting case of conflict between KB and triggering information. In fact, the amnesic (forgetful) revision operator defined by $B * \alpha = \mathrm{Cn}(\alpha)$ fulfils all AGM postulates though it is clearly not minimal as it completely deletes the sentences of the knowledge base B.

The relevance postulates of Hansson [16] and of Parikh [26] are two different possibilities that remedy the unwanted property of amnesic revision. Relevance postulates specify that only those sentences of the initial KB are allowed to be eliminated that are potential candidates for the conflict of the KB and the trigger. These kind of postulates constrain the revision result by an approximation from below in the sense that they say which set of sentences X (namely those not relevant for the conflict) have to be in the (set of consequences of the) revision result: $X \subseteq \mathrm{Cn}(B * \alpha)$. Note that the AGM postulate called Expansion 2 (Exp 2) constrains the result only in the trivial case where the trigger does not contradict the belief set. (AGM formulated their postulates for logically closed KBs which they call *belief sets*.)

(Exp 2) If $\neg\alpha \notin B$, then $\mathrm{Cn}(B \cup \alpha) \subseteq B * \alpha$.

The relevance postulate of Hansson [16] is formulated for arbitrary, i.e. not necessarily logically closed, sets of sentences B called belief bases. The postulate says in words: If a sentence β of the belief base B is not contained in the revision result $B * \alpha$, then it would lead to an inconsistency if it were added to a consistent extension B' of the revision result.

(Rel-H) If $\beta \in B$ and $\beta \notin B * \alpha$, then there is a set B', such that:

- $B * \alpha \subseteq B' \subseteq B \cup \{\alpha\}$;
- B' is consistent;
- $B' \cup \{\beta\}$ is not consistent.

Though this postulate formulates a moderate relevance condition for belief base operators it is not an adequate postulate for the intended integration scenario. In this scenario, it is not individual sentences which cause a conflict but different uses of (concept or role or more generally predicate but not constant) symbols in the knowledge base B and the trigger β. And indeed, the reinterpretation based operators defined below do not fulfil this postulate.

Example 1 *Let, e.g., be given a knowledge base according to which we think that the media pr_1, pr_2, which are published in some proceedings are articles: $B = \{Article(pr_1), Article(pr_2)\}$. The trigger $\alpha = \neg Article(pr_1)$ stems from an agent who has a different understanding of 'article' according to which only publications in journals (but not proceedings) are articles. An appropriate revision result $B * \alpha$ would not only delete $Article(pr_1)$ but also $Article(pr_2)$; because the next time the sender sends a trigger containing $Article$ negatively, namely $\neg Article(pr_2)$, a conflict will occur. But this operator $*$ does not fulfil (Rel-H). As we will show below we can formulate a radically adapted version of this relevance postulate that is fulfilled by the reinterpretation operators.*

A completely different relevance postulate, which is more symbol-oriented and hence works equally for belief-base revision and belief-set revision, was formulated by Parikh [26] and further developed by him and colleagues [6, 7], as well as generalised by [20] and [19]. The idea rests on representing a KB B equivalently with KB components with pairwise disjoint symbols sets $\mathcal{V}_n$. Then a formula β is considered to be relevant for the revision with the trigger α iff β and α have symbols in one of the symbol sets $\mathcal{V}_n$ in common.

Formally, let $\mathcal{V}$ be an FOL vocabulary and $\mathbf{V} = \{\mathcal{V}_n\}_{n \in I}$ be a partition of $\mathcal{V}$. $\mathbf{V}$ is a *splitting* of a KB B iff there exists a family of KBs $\{B_n\}_{n \in I}$ s.t.: $\mathcal{V}(B_n) \subseteq \mathcal{V}_n$ and $\bigcup\{B_n\}_{n \in I} \equiv B$ [20]. Ordering splittings as partitions in the usual way, one can prove that for every KB B there is always a unique finest splitting of B [20, 26]. Now let B be a consistent KB and $\mathbf{V} = \{\mathcal{V}_n\}_{n \in I}$ the unique finest splitting $\mathcal{V}$ of B. A formula β is *irrelevant* w.r.t. to the revision of B with trigger α—β is *irrelevant for α modulo B for short*—iff for all $\mathcal{V}_n \in \mathbf{V}$: $\mathcal{V}_n \cap \mathcal{V}(\beta) = \emptyset$ or $\mathcal{V}_n \cap \mathcal{V}(\alpha) = \emptyset$. The relevance criterion of Parikh now reads:

(Rel-P) If β is irrelevant for α modulo B, then $\beta \in \mathrm{Cn}(B * \alpha)$.

Parikh's criterion (Rel-P) is not strong enough to exclude a kind of semantic integration operation that in some sense is too sceptical.

Example 2 *Think again of an integration scenario where the sender has a stronger notion of article than the receiver. Assume that the receiver's KB is* $B = \{Article(pr_1), Article(pr_2), \neg Article(bo_1)\}$, *which in particular says that the publication* bo_1 *is not an article, and the trigger stemming form the sender is* $\alpha = \neg Article(pr_1)$. *Consider the following integration operator* $*$*: For arbitrary KBs* B *and trigger* α *the operator renames concept and role symbols* s *of the receiver's KB into new fresh symbols* s' *in order to regain consistency. In case of this example only the occurrences of* $Article$ *in* B *are renamed into* $Article'$ *and one gets* $B * \alpha = \{Article'(pr_1), Article'(pr_2), \neg Article'(bo_1), \neg Article(pr_1)\}$. *This operator* $*$ *clearly fulfils the criterion (Rel-P). But we lose the information of* B *that the book* bo_1 *is not an* $Article$. *Hence (Rel-P) is not a relevance criterion that prohibits all too sceptical (though symbol oriented) revision.*

The relevance postulates cover only one aspect of minimality, but completely miss the other aspect of minimality which is to constrain the (consequences of the) revision result from above. That is, one has to prescribe a set X such that $\mathrm{Cn}(B * \alpha) \subseteq X$. In classical AGM belief revision [1] the first expansion postulate (Exp 1) constrains the revision result only in the uninteresting case where α does not contradict B. In the more interesting case of contradiction, $\mathrm{Cn}(B \cup \alpha)$ is the set of all sentences, hence the postulate becomes vacuous.

(Exp 1) $B * \alpha \subseteq \mathrm{Cn}(B \cup \alpha)$.

For belief base revision, the (revised) knowledge base and the result do not have to be logically closed. Hence the postulate corresponding to (Exp 1), called inclusion postulate, really results in a approximation from above—thereby hampering all too creative base revision.

(Incl) $B*\alpha \subseteq B \cup \alpha$.

But for the integration scenario, belief base revision is not the means of choice as its results depend on the syntactic representation of the belief bases. For example, if the result of the revision of $\{Article(pr_1), \neg Article(bo_1), \neg Article(bo_2)\}$ with $\neg Article(pr_1)$ results in $\{\neg Article(bo_1) \wedge \neg Article(bo_2)\}$, this should be considered to be a non-creative (acceptable) revision result, though (Incl) is not fulfilled. Hence, we will define a different form of inclusion postulate that abstracts from the syntactic representations of the knowledge bases. Thereby we will have described a postulate for operators on the knowledge level [22], in which ontologies are first-class citizens.

4 THE POSTULATE OF REINTERPRETATION RELEVANCE

For the following we will assume that B is a predicate logical KB without the identity and function symbols, i.e., B is a finite set of sentences in first order (predicate) logic without identity and functional symbols. The new relevance postulate starts off from Hansson's relevance postulate (Rel-H) and adapts it in the direction of making it more symbol-oriented. The main technical tool for the adaptation is the concept of a prime implicate, which roughly represents a most atomic component of the KB. Though it is the different use of symbols that leads to conflicts in our integration scenario, it is sentences that make up a conflict. Hence, by representing a KB in a specific normal form by its implied prime implicates, one gets a fine-grained means for identifying the real culprit symbols for conflicts: just identify the prime implicates in which the symbols are contained and which are involved in a conflict. While the notion of prime implicate is omnipresent for propositional logic [3] and has been exploited for the definitions of propositional revision operators [5, 25, 31], there is no real semantic notion of prime implicate for FOL that deserves this term (but compare the prime implicate definition for modal logics in [4]), and there is no approach that uses prime implicates in the postulates. We will work with a more syntactic notion of prime implicates and use it for the (satisfiably) equivalent representations of KBs.

The core idea of the new relevance theorem is this: A sentence β entailed by B is allowed to be eliminated from the integration result if there is a related sentence ϵ of the normal form of B that together with other formulas of the normal form leads to a contradiction. The kind of relatedness between β and ϵ will be further specified below. We now formalise the notions in order to formulate the relevance postulate.

A FOL formula α is universal iff α is equivalent to a formula in prenex form containing only all-quantifiers $\forall$. A universal formula of the form $\forall x_1 \ldots \forall x_n (li_1 \vee \cdots \vee li_m)$, where the li_j are literals with variables in $\{x_1, \ldots, x_n\}$, is a *FOL clause*. An FOL clause $\alpha_1 = \forall x_1 \ldots \forall x_n \beta$ is a *(proper) subclause* of a FOL clause α_2, iff α_2 is of the form $\alpha_2 = \forall y_1 \ldots \forall y_n \delta$, where all x_i are among the y_j and the set of literals in β is a (proper) subset of the literals in δ.

Let X be a set of universal formulas. The set of *FOL clauses of X w.r.t. to a vocabulary* $\mathcal{V}$, $\mathrm{Cl}^{\mathcal{V}}(X)$, is the set of all FOL clauses in $\mathrm{Sent}(\mathcal{V})$ entailed by X. For formulas α let $\mathrm{Cl}^{\mathcal{V}}(\alpha) = \mathrm{Cl}^{\mathcal{V}}(\{\alpha\})$. If X is an arbitrary set of FOL sentences, let X^* be the result of skolemizing every sentence in X (with fresh constants). Let $\mathcal{V}_{\text{sk}}$ be the set of used skolem symbols. The set of *FOL clause of X w.r.t. $\mathcal{V}$ and skolem symbols* $\mathcal{V}_{\text{sk}}$ is defined by $\mathrm{Cl}^{\mathcal{V} \cup \mathcal{V}_{\text{sk}}}(X^*)$.

Now we can define the set of *FOL prime implicates* of a set of universal formula X w.r.t. $\mathcal{V}$ as the set of non-tautological clauses of X for which there is no proper subclause in $\mathrm{Cl}^{\mathcal{V}}(X)$.

$$\mathrm{PI}^{\mathcal{V}}(X) \quad = \quad \{pr \in \mathrm{Cl}^{\mathcal{V}}(X) \mid pr \text{ is non-tautological and has no proper subclauses in } \mathrm{Cl}^{\mathcal{V}}(X)\}$$

The notion of an FOL prime implicate leads to a logically equivalent characterisation of sets X containing only universal formulas.

Proposition 1 *Let* $\mathcal{V}$ *be a predicate logical vocabulary. For every set* X *of universal formulas* X *with* $\mathcal{V}(X) \subseteq \mathcal{V}$ *we have:* $X \equiv \mathrm{PI}^{\mathcal{V}}(X)$.

The notion of relatedness mentioned above is explicated technically by the (semantically) positive and negative occurrences of symbols; it says that β and ϵ are related w.r.t. to a symbol P occurring in both iff P occurs in the same polarity in both sentences or at least mixed in one of the sentences.

Definition 1 *Let* P *be a predicate symbol which occurs properly in* β *and* ϵ. β *and* ϵ *are called* related w.r.t. P *iff a) either* $mixOcc(P, \epsilon)$ *or* $mixOcc(P, \beta)$*; or b)* $posOcc(P, \epsilon)$ *and* $posOcc(P, \beta)$*; or c)* $negOcc(P, \epsilon)$ *and* $negOcc(P, \beta)$.

The new relevance postulate (Rel-R) which we call the postulate of *reinterpretation relevance* now has the following form:

(Rel-R) Let be given a vocabulary $\mathcal{V}$, an FOL KB B over $\mathcal{V}$, an FOL sentence α over $\mathcal{V}$ and an FOL clause β over $\mathcal{V}$. Let B^* be a skolemization of $\bigwedge B$ with skolem constants from $\mathcal{V}_{\text{sk}}$.
If $B \models \beta$ and $B * \alpha \not\models \beta$, then there is a set X and a sentence $\epsilon \in X$ s.t.:

1. $X \subseteq \text{PI}^{\mathcal{V} \cup \mathcal{V}_{\text{sk}}}(B^*)$;
2. $X \cup \{\alpha\}$ is inconsistent;
3. $(X \setminus \{\epsilon\}) \cup \{\alpha\}$ is consistent and
4. ϵ is related with β w.r.t. a predicate symbol P.

In words the postulates says the following: If there is a sentence β (in fact we constrain β to be a clause) which follows from the original KB B but is not contained in the integration result $B * \alpha$, then there must be a good reason for excluding it from the result. The reason for the exclusion is explained by a reference to the prime implicate form of B: There is a sentence ϵ related to β such that its addition to a subset $X \setminus \{\epsilon\}$ of the prime implicate form contradicts α. Hence, the exclusion is not necessarily justified by identifying β as a culprit for the conflict but (possibly) another related sentence ϵ. Note that the set $X \setminus \{\epsilon\}$ has the role of B' in the relevance postulate (Rel-H) of Hansson. Though (Rel-R) expresses a very weak form of relevance, it prohibits revision operators like those of Ex. 2.

Example 3 *As in Ex. 2 assume that the KB has the form* $B = \{Article(pr_1), Article(pr_2), \neg Article(bo_1)\}$ *and the trigger is* $\alpha = \neg Article(pr_1)$. *Clearly* $\text{PI}^{\mathcal{V} \cup \mathcal{V}_{\text{sk}}}(B^*) = B^* = B$. *Let* $\beta = \neg Article(bo_1)$. *Then* $B \models \beta$ *and* $B * \alpha \not\models \beta$. *But for the predicate* $Article$ *there is no* $X \subseteq \text{PI}^{\mathcal{V} \cup \mathcal{V}_{\text{sk}}}(B^*)$ *that fulfils the conditions of (Rel-R) because the only* β*-related prime implicate is* $\neg Article(bo_1)$ *which is not involved in a conflict.*

5 AN EXTENDED INCLUSION POSTULATE

We further exploit the idea of prime implicates to define a postulate that captures the other aspect of minimal integration where one constrains the (consequences of the integration) result from above. The idea, in principle, is to enrich the given KB B to an equivalent set $\text{Enr}(B)$ that contains enough consequences of B in order to identify the real potential culprits in the integration process. A typical example for an enrichment operator is the disjunctive closure of a belief base according to which a belief base is closed up with all (finite) disjunctions of sentences in it [15]. The general schema of the extended inclusion axiom is the following:

(Incl-ES) For all α there is an $X \subseteq \text{Enr}(B)$ such that $X \cup \{\alpha\} \not\models \bot$, and for all β: If $B * \alpha \models \beta$, then $X \cup \{\alpha\} \models \beta$.

This schema says: There is a subset of the enrichment of B such that all sentences β entailed by the integration result follow from a subset X of the enrichment together with the trigger α. Instantiations of this schema with different enrichment operators Enr result in different extended inclusion postulates whose usability relies heavily on the properties of Enr. If, e.g., Enr is the identity, we get an all too strict inclusion postulate. If Enr is Cn, we get an all too weak inclusion postulate. That means, the good candidates for Enr lie in between the identity and the consequence operator, and hence one should ensure that $\text{Enr}(B) \equiv B$. As we allow the enrichment also to introduce new symbols (like those needed for skolemization) we weaken this goodness criterion to the restriction that B and $\text{Enr}(B)$ should be equivalent w.r.t. to the old vocabulary $\mathcal{V}$. The enrichment operator Enr we will use in the following is an operator that enriches B with prime implicates of its skolemization.

$$\text{Enr}(B) = B \cup \text{PI}^{\mathcal{V} \cup \mathcal{V}_{\text{sk}}}(B^*)$$

And in fact, though the enriched KB $\text{Enr}(B)$ is not equivalent to B, it is at least equivalent w.r.t. to the non-skolem symbols.

Proposition 2 *For (finite) KBs* B *over* $\mathcal{V}$*:*

$$\text{Cn}^{\mathcal{V}}(B) = \text{Cn}^{\mathcal{V}}(\text{Enr}(B))$$

We call the postulate that results from (Incl-ES) by instantiating the parameter Enr by $\text{Enr}(B) = B \cup \text{PI}^{\mathcal{V} \cup \mathcal{V}_{\text{sk}}}(B^*)$ the extended inclusion postulate (Incl-E).

6 REINTERPRETATION OPERATORS

The extended relevance postulate and inclusion postulate are intended to specify minimal changes of revision-like operators which are used in a particular semantic integration scenario described in the introduction. In this section, we recapitulate the definition of operators of this kind [11, 24] and show that they fulfil the new postulates. Other postulates that are fulfilled by these operators (cf. ([24]) will not be discussed in this paper. The construction of the operators mimics the construction of the propositional revision operators of [9].

The integration operator to be defined in the following is denoted by $\circ$ and is called a reinterpretation operator. (In [24] it is called weak reinterpretation operator of type 2, but as we define only this reinterpretation operator, here we do not use the additional specifications.) $\circ$ is a binary operator with a finite FOL KB as left and an FOL sentence α as right argument. Before giving the technical definition, the main construction idea will be illustrated with the KB and the trigger of Ex. 2.

Example 4 *Let* $B = \{Article(pr_1), Article(pr_2), \neg Article(bo_1)\}$ *and the trigger* $\alpha = \neg Article(pr_1)$. *The reinterpretation operator* $\circ$ *results in the following KB:*

$$\begin{aligned} B \circ \alpha \quad = \quad & \{Article'(pr_1), Article'(pr_2), \neg Article'(bo_1), \\ & \neg Article(pr_1), \\ & \forall x(Article(x) \rightarrow Article'(x))\} \end{aligned}$$

The conflict between B *and* α *is traced back to ambiguous use of symbols. As we assume that only predicate symbols (and not constants) may be used ambiguously, the conflict can only be caused by different uses of the unary predicate* $Article$. *The receiver (holder of* B*) gives priority to the sender's use of* $Article$ *over his use of* $Article$, *and hence he adds* $\neg Article(pr_1)$ *into the result* $B \circ \alpha$. *Its own use of* $Article$ *is internalized, i.e., all occurrences of* $Article$ *in* B *are substituted by a new symbol* $Article'$. *This step of internalization will also be called the step of dissociation or disambiguation as the uses of* $Article$ *according to sender and receiver are put apart. But as we assumed that in the integration scenario the uses of* $Article$ *by sender and receiver are similar, the receiver adds hypotheses on the semantical relatedness (bridging axioms, cf. [23]) of his and the sender's use of* $Article$. *The hypothesis in this case is* $\forall x(Article(x) \rightarrow Article'(x))$ *which says that articles in the sender's sense are also articles in the receiver's sense. Note that because of this hypothesis the result* $B \circ \alpha$ *entails the assertion* $\neg Article(bo_1)$ *from the initial KB* B. *The other direction of the hypothesis, namely* $\forall x(Article'(x) \rightarrow Article(x))$ *cannot be added to the result as it would lead to a contradiction.*

So the general construction for the reinterpretation operators in case of conflict is first to disambiguate the symbols involved in a conflict and second add bridging axioms. Technically the disambiguation is realised by uniform substitutions called *ambiguity compliant resolution substitutions*, $\mathrm{AR}(\mathcal{V}, \mathcal{V}')$ for short. Here, we assume $\mathcal{V} \cap \mathcal{V}' = \emptyset$ where $\mathcal{V}'$ is the set of symbols used for internalization. The substitutions in $\mathrm{AR}(\mathcal{V}, \mathcal{V}')$ get as input a non-logical symbol in $\mathcal{V}$ (in case of this paper: a predicate symbol) and map it either to itself or to a new non-logical symbol (of the same type) in $\mathcal{V}'$. In our case we only consider the substitution of predicate symbols. The set of symbols $s \in \mathcal{V}$ for which $\sigma(s) \neq s$ is called the support of σ and is denoted $\mathrm{supp}(\sigma)$. A substitution with support S is also denoted by σ_S. For substitutions $\sigma_1, \sigma_2 \in \mathrm{AR}(\mathcal{V}, \mathcal{V}')$ we define an ordering by: $\sigma_1 \leq \sigma_2$ iff $\mathrm{supp}(\sigma_1) \subseteq \mathrm{supp}(\sigma_2)$. $\mathrm{AR}(\mathcal{V}, \mathcal{V}')$ can be partitioned into equivalence classes of substitutions that have the same support. We assume that for every equivalence class a representative substitution $\Phi(S) \in ars(\mathcal{V}, \mathcal{V}')$ with support S is fixed. Φ is called a *disambiguation schema*.

In the general case, there may be more than one predicate symbol which has to be disambiguated in order to get consistency; and even more, there may be many different sets of symbols for which a disambiguation leads to consistency. These sets are called minimal conflict symbol sets and are defined formally as follows:

Definition 2 *Let B be an FOL KB over $\mathcal{V}$ and α an FOL sentence over $\mathcal{V}$. The set of* minimal conflicting symbols sets, *$\mathrm{MCS}(B, \alpha)$, is defined by:*

$$\mathrm{MCS}(B,\alpha) = \{S \subseteq \mathcal{V} \mid \text{There is a } \sigma_S \in \mathrm{AR}(\mathcal{V},\mathcal{V}'), \text{ s.t. } B\sigma_S \cup \{\alpha\} \text{ is consistent, and for all } \sigma_R \in \mathrm{AR}(\mathcal{V},\mathcal{V}') \text{ with } \sigma_R < \sigma_S\ B\sigma_R \cup \{\alpha\} \text{ is not consistent. } \}$$

As no symbol set in $\mathrm{MCS}(B, \alpha)$ is a better candidate then the other, we assume that a selection function γ_1 selects the good candidates: $\gamma_1(\mathrm{MCS}(B, \alpha)) \subseteq \mathrm{MCS}(B, \alpha)$. In the end, the symbol set $S^{\#} = \bigcup \gamma_1(\mathrm{MCS}(B, \alpha))$ is the set of symbols which will be internalized.

In the second step, the disambiguated symbols of $S^{\#}$ are related by bridging axioms. Depending on what kind of bridging axioms are chosen, different integration operators result. Here, we choose a very conservative simple class of initial bridging axioms called *simple bridging axioms*. (For other types of bridging axioms see [24] and [11].) Let be given a substitution $\sigma = \sigma_S \in \mathrm{AR}(\mathcal{V}, \mathcal{V})$ with support $S \subseteq \mathcal{V}$. Let P be an n-ary predicate symbol in S, $\sigma(P) = P'$ and let $\vec{x} = x_1, \dots, x_n$. Then define $\overrightarrow{P} = \forall \vec{x}(P(\vec{x}) \rightarrow P'(\vec{x}))$ and $\overleftarrow{P} = \forall \vec{x}(P'(\vec{x}) \rightarrow P(\vec{x}))$.

Definition 3 *Let $\sigma = \sigma_S \in \mathrm{AR}(\mathcal{V}, \mathcal{V})$ for $S \subseteq \mathcal{V}$. The set of simple bridging axioms w.r.t. σ is* $\mathrm{BA}(\sigma) = \{\overrightarrow{P}, \overleftarrow{P} \mid P \in S\}$.

In case of conflict, not all bridging axioms of $\mathrm{BA}(S^{\#})$ can be added to the integration result (compare Ex. 4). Hence, we search for subsets that are compatible with the union of the internalized KB and the trigger, $B\sigma \cup \{\alpha\}$. That means, possible candidate sets of bridging axioms can be described by dual remainder sets (see section on logical preliminaries) as $\mathrm{BA}(\sigma)\top(B\sigma \cup \{\alpha\})$. Again, as there is no preference for one candidate over the other we assume that a second selection function γ_2 is given with $\gamma_2(\mathrm{BA}(\sigma)\top(B\sigma \cup \{\alpha\})) \subseteq (\mathrm{BA}(\sigma)\top(B\sigma \cup \{\alpha\})$. The intersections of the selected bridging axioms is the set of bridging axioms added to the integration result. (Compare this with the partial meet revision functions of AGM [1]). The reinterpretation operator $\circ = \circ^{\overline{\gamma}}$ now is defined as follows:

Definition 4 *Let $\mathcal{V}$ be a predicate logical vocabulary, $\mathcal{V}'$ a disjoint predicate logical vocabulary (for internalization) and let be given a disambiguation scheme Φ. Moreover let be given selection functions γ_1, γ_2 and for short let $\overline{\gamma} = (\gamma_1, \gamma_2)$. For any FOL KB B and FOL sentence α over $\mathcal{V}$ let $S^{\#} = \bigcup \gamma_1(\mathrm{MCS}(B, \alpha))$ and $\sigma = \Phi(S^{\#})$. Then the* reinterpretation operator $\circ = \circ^{\overline{\gamma}}$ *is defined by*

$$B \circ \alpha \quad = \quad \sigma(B) \cup \{\alpha\} \cup \bigcap \gamma_2\big(\mathrm{BA}(\sigma)\top(\sigma(B) \cup \{\alpha\})\big)$$

It can easily be checked that this definition of $\circ$ gives the results in Ex. 4 (for any pair of selection functions γ_1, γ_2).

7 REINTERPRETATION OPERATORS ARE MINIMAL SEMANTIC INTEGRATION OPERATORS

We now justify the introduction of the reinterpretation operators by proving that they fulfil the reinterpretation postulate and the extended inclusion postulate. The main component in the proofs are propositions that explicate the interaction of the internalization and of the bridging axioms with the prime implicates implied by the KB B. The first main proposition is explicated in the following:

Proposition 3 *Let be given vocabularies $\mathcal{V}$ and $\mathcal{V}'$ with $\mathcal{V} \cap \mathcal{V}' = \emptyset$. Let B be a set of universal formula in FOL (without identity and function symbols) over $\mathcal{V}$, let σ be a substitution of predicate symbols P by new symbols $\sigma(P) \in \mathcal{V}'$ and let $\mathrm{PI}(\cdot) = \mathrm{PI}^{\mathcal{V} \cup \mathcal{V}'}(\cdot)$. Then:*

$$\mathrm{Cn}^{\mathcal{V}}(\mathrm{PI}(B\sigma)) = \mathrm{Cn}^{\mathcal{V}}(\mathrm{PI}(B\sigma) \cap \mathrm{Sent}(\mathcal{V}))$$

If a KB B is internalized w.r.t. to some symbols (those in the support of σ), then some of the original consequences of B are lost, and hence this is also true for the equivalent set of prime implicates of $B\sigma$ over the (larger) vocabulary $\mathcal{V} \cup \mathcal{V}'$. But remarkably, according to this proposition, if we restricted the prime implicates to those containing only symbols of $\mathcal{V}$, the loss of $\mathcal{V}$-consequences of B does not become bigger. That means that in order to register losses of $\mathcal{V}$-consequences of B we can stick to the prime implicates of B.

While this proposition hints to the interaction of prime implicates with the internalization, the following proposition talks about their interaction with simple bridging axioms. The proposition refers to the notion of an admissible skolemization. Let $B^* = \forall \tilde{x}_1 \dots \forall \tilde{x}_m \tilde{B}$ be a skolemization of B with skolem constants not in $\mathcal{V}(B \cup B\sigma)$. Then $B^*\sigma = \forall \tilde{x}_1 \dots \forall \tilde{x}_m \tilde{B}\sigma$ is a skolemization of $B\sigma$. Let $\forall z \tilde{ba}$ be a prenex form of some set of bridging axioms $ba \subseteq \mathrm{BA}(\sigma)$. Then $(B\sigma \cup ba)^*$ is called an B^**- admissible skolemization* of $B\sigma \cup ba$ iff it has the form $(B\sigma \cup ba)^* = \forall z \forall \tilde{x}_1 \dots \forall \tilde{x}_m (\tilde{B}\sigma \wedge \tilde{ba})$.

Proposition 4 *Let $\mathcal{V}$, $\mathcal{V}'$, $\mathcal{V}_{\mathrm{sk}}$ be pairwise disjoint vocabularies. Let B be a KB over $\mathcal{V}$ and σ be a substitution of predicate symbols P by new predicate symbols $\sigma(P) \in \mathcal{V}'$. Let $ba \subseteq \mathrm{BA}(\sigma)$ be a subset of bridging axioms and $(B\sigma \cup ba)^*$ be a B^*-admissible skolemization of $B\sigma \cup ba$ with skolem constants from $\mathcal{V}_{\mathrm{sk}}$; then:*

$$\mathrm{PI}^{\mathcal{V} \cup \mathcal{V}' \cup \mathcal{V}_{\mathrm{sk}}}((B\sigma \cup ba)^*) \cap \mathrm{Sent}(\mathcal{V} \cup \mathcal{V}(B^*)) \subseteq \mathrm{PI}^{\mathcal{V} \cup \mathcal{V}_{\mathrm{sk}}}(B^*)$$

This proposition says that the internalization with symbols from $\mathcal{V}'$ and the addition of bridging axioms to the KB does not enlarge the capability of prime implicates to entail sentences not containing internal symbols. Again, that means that the original prime implicates of the KB B can be used as indicators for possible conflicts. Note that a corresponding proposition for more complex bridging axioms may not hold.

Using these propositions one can show the desired theorem.

Theorem 1 *The reinterpretation operators according to Definition 4 fulfil the postulates of reinterpretation relevance (Rel-R) and extended inclusion (Incl-ES).*

We give a proof of the theorem based on the propositions above and the following proposition which is part of the folklore.

Proposition 5 *Let β be an FOL formula over $\mathcal{V}$ and β^* be a skolemization with constants not in $\mathcal{V}$. Then $\mathrm{Cn}^{\mathcal{V}}(\beta) = \mathrm{Cn}^{\mathcal{V}}(\beta^*)$.*

Proof that postulate (Rel-R) is fulfilled

We need the following lemma which can be proved by considering resolution. In the lemma we use the auxiliary boolean function g; let P be an n-ary predicate symbol and β be an arbitrary sentence. $g(ba, \beta)$ holds iff P occurs in β in a polarity corresponding to its occurrence in the simple bridging axiom ba.

$$g(ba, \beta) = \begin{cases} posOccOrNot(P, \beta), & \text{if } ba = \overleftarrow{P} \\ negOccOrNot(P, \beta), & \text{if } ba = \overrightarrow{P} \end{cases}$$

Lemma 1 *Let $S = \{P_1, \dots, P_n\}$ be a set of pairwise disjoint predicate symbols from a vocabulary $\mathcal{V}$, $\sigma = [P_1/P_1', \dots, P_n/P_n']$ an injective substitution with $P_i' \in \mathcal{V} \setminus S$, $1 \le i \le n$. Let $\mathcal{V}_n = \mathcal{V} \setminus \{P_1', \dots, P_n'\}$. Let B be a KB with $\mathcal{V}(B) \subseteq \mathcal{V}_n$ and $ba \subseteq \mathrm{BA}(\sigma)$ a set of bridging axioms of the form $ba(P_i) \in \{\overrightarrow{P_i}, \overleftarrow{P_i}\}$, $1 \le i \le n$. Let $(B\sigma \cup ba)^*$ be an B^*-admissible skolemization of $B\sigma \cup ba$ with skolem constants from $\mathcal{V} \setminus \mathcal{V}(B \setminus \mathcal{V}(B\sigma)$. Last but not least let $U \subseteq S$ be the set of symbols $P_i \in S$ such that $\{\overrightarrow{P_i}, \overleftarrow{P_i}\} \subseteq ba$. Then*

$$\begin{aligned} Cl^{\mathcal{V}_n}((O\sigma \cup B)^*) \quad = \quad & \{\beta \in Cl^{\mathcal{V}_n}(O^*) \mid \textit{There is an } \epsilon \textit{ with:} \\ & \epsilon \in Cl^{\mathcal{V}_n}((B\sigma \cup ba)^*); \\ & \epsilon \models \beta; \\ & \epsilon \textit{ has no symbol of } S \setminus \mathcal{V}(ba) \textit{ and for all} \\ & P_i \in (S \cap \mathcal{V}(ba)) \setminus U\textit{: } g(ba(P_i), \epsilon)\} \end{aligned}$$

Let B_{res} abbreviate $B \circ \alpha = B\sigma \cup ba \cup \{\alpha\}$ for a subset $ba \subseteq BA(\sigma)$. Let $B_{\mathrm{res}} \not\models \beta$ and $B \models \beta$. Because of Prop. 5 it holds that $B^* \models \beta$ and $(B\sigma \cup ba)^* \not\models \bot$. Because of Lemma 1 it follows that there is a predicate symbol P in β s.t.: P does not occur in ba or we have $ba(P) \in ba$, but not $g(ba(P), \beta)$. I consider only the latter case as the former can be reduced to it. W.lo.g. let $ba(P) = \overleftarrow{P}$. That means that P either occurs mixed in β or positively.

That $\overleftarrow{P}$ is not contained in the integration result means that there is a subset $ba' = \{ba(P_1), \dots, ba(P_k)\} \subseteq \mathrm{BA}(\sigma)$ of the bridging axioms s.t.

$$Y := B\sigma \cup ba'$$

is compatible with α but

$$Z := B\sigma \cup ba' \cup \{\overleftarrow{P}\}$$

is not compatible with α. Hence $\neg\alpha \notin \mathrm{Cn}^{\mathcal{V}}(Y)$, whilst $\neg\alpha \in \mathrm{Cn}^{\mathcal{V}}(Z)$. Let Y^* and Z^* be B^*-admissible skolemizations with skolem constants in $\mathcal{V}_{\mathrm{sk}}$. With Prop. 5 it follows $\neg\alpha \notin \mathrm{Cn}^{\mathcal{V}}(Y^*)$, whilst $\neg\alpha \in \mathrm{Cn}^{\mathcal{V}}(Z^*)$. Because of Prop. 1 it follows

$$\begin{aligned} \neg\alpha \quad & \notin \quad \mathrm{Cn}^{\mathcal{V}}(\mathrm{PI}^{\mathcal{V} \cup \mathcal{V}' \cup \mathcal{V}_{\mathrm{sk}}}(Y^*)), \text{ but} && (1) \\ \neg\alpha \quad & \in \quad \mathrm{Cn}^{\mathcal{V}}(\mathrm{PI}^{\mathcal{V} \cup \mathcal{V}' \cup \mathcal{V}_{\mathrm{sk}}}(Z^*)) && (2) \end{aligned}$$

Because of Prop. 3 we have further

$$\begin{aligned} \mathrm{Cn}^{\mathcal{V} \cup \mathcal{V}_{\mathrm{sk}}}(Y^*) \quad & = \quad \mathrm{Cn}^{\mathcal{V} \cup \mathcal{V}_{\mathrm{sk}}}(\mathrm{PI}^{\mathcal{V} \cup \mathcal{V}' \cup \mathcal{V}_{\mathrm{sk}}}(Y^*) \cap \mathrm{Sent}(\mathcal{V} \cup \mathcal{V}_{\mathrm{sk}})) \\ \mathrm{Cn}^{\mathcal{V} \cup \mathcal{V}_{\mathrm{sk}}}(Z^*) \quad & = \quad \mathrm{Cn}^{\mathcal{V} \cup \mathcal{V}_{\mathrm{sk}}}(\mathrm{PI}^{\mathcal{V} \cup \mathcal{V}' \cup \mathcal{V}_{\mathrm{sk}}}(Z^*) \cap \mathrm{Sent}(\mathcal{V} \cup \mathcal{V}_{\mathrm{sk}})) \end{aligned}$$

Intersecting both sides of the equation with $\mathrm{Sent}(\mathcal{V})$ results in the equations:

$$\begin{aligned} \mathrm{Cn}^{\mathcal{V}}(Y^*) \quad & = \quad \mathrm{Cn}^{\mathcal{V}}(\mathrm{PI}^{\mathcal{V} \cup \mathcal{V}' \cup \mathcal{V}_{\mathrm{sk}}}(Y^*) \cap \mathrm{Sent}(\mathcal{V} \cup \mathcal{V}_{\mathrm{sk}})) \\ \mathrm{Cn}^{\mathcal{V}}(Z^*) \quad & = \quad \mathrm{Cn}^{\mathcal{V}}(\mathrm{PI}^{\mathcal{V} \cup \mathcal{V}' \cup \mathcal{V}_{\mathrm{sk}}}(Z^*) \cap \mathrm{Sent}(\mathcal{V} \cup \mathcal{V}_{\mathrm{sk}})) \end{aligned}$$

Therefore with (1) and (2) one can infer that

$$\begin{aligned} \neg\alpha \quad & \notin \quad \mathrm{Cn}^{\mathcal{V}}(\mathrm{PI}^{\mathcal{V} \cup \mathcal{V}' \cup \mathcal{V}_{\mathrm{sk}}}(Y^*) \cap \mathrm{Sent}(\mathcal{V} \cup \mathcal{V}_{\mathrm{sk}})) \\ \neg\alpha \quad & \in \quad \mathrm{Cn}^{\mathcal{V}}(\mathrm{PI}^{\mathcal{V} \cup \mathcal{V}' \cup \mathcal{V}_{\mathrm{sk}}}(Z^*) \cap \mathrm{Sent}(\mathcal{V} \cup \mathcal{V}_{\mathrm{sk}})) \end{aligned}$$

Because of Prop. 4 the sets $X_1 = \mathrm{PI}^{\mathcal{V} \cup \mathcal{V}' \cup \mathcal{V}_{\mathrm{sk}}}(Y^*) \cap \mathrm{Sent}(\mathcal{V} \cup \mathcal{V}_{\mathrm{sk}})$ and $X_2 = \mathrm{PI}^{\mathcal{V} \cup \mathcal{V}' \cup \mathcal{V}_{\mathrm{sk}}}(Z^*) \cap \mathrm{Sent}(\mathcal{V} \cup \mathcal{V}_{\mathrm{sk}})$ are prime implicates of B^* with $X_1 \subseteq X_2$. Choose an X such that $X_1 \subseteq X \subseteq X_2$ and X is inclusion minimal w.r.t. the property that $\neg\alpha \in \mathrm{Cn}^{\mathcal{V}}(X)$. Such an X exists, as for X_2 one has $\neg\alpha \in \mathrm{Cn}^{\mathcal{V}}(X_2)$. X must contain prime implicates in which P occurs positively or in mixed form; otherwise we would have $X_1 = X_2$. Hence there is also an ϵ which is related to β w.r.t. P. So all conditions of (Rel-R) are fulfilled.

Proof that postulate (Incl-E) is fulfilled

Assume that $B \circ \alpha = B\sigma \cup ba \cup \{\alpha\}$ for some set of bridging axioms $ba \subseteq \mathrm{BA}(\sigma)$. Now we have the following chain of equations:

$$\begin{aligned} \mathrm{Cn}^{\mathcal{V}}(B\sigma \cup ba) \quad & \overset{\text{Prop. 5}}{=} \quad \mathrm{Cn}^{\mathcal{V}}((B\sigma \cup ba)^*) \\ & \overset{\text{Prop. 1}}{=} \quad \mathrm{Cn}^{\mathcal{V}}(\mathrm{PI}^{\mathcal{V} \cup \mathcal{V}' \cup \mathcal{V}_{\mathrm{sk}}}((B\sigma \cup ba)^*)) \\ & \overset{\text{Prop. 3}}{=} \quad \mathrm{Cn}^{\mathcal{V}}(\mathrm{PI}^{\mathcal{V} \cup \mathcal{V}' \cup \mathcal{V}_{\mathrm{sk}}}((B\sigma \cup ba)^*) \\ & \qquad \cap \mathrm{Sent}(\mathcal{V} \cup \mathcal{V}(B^*))) \end{aligned}$$

Let $X = \mathrm{PI}^{\mathcal{V} \cup \mathcal{V}' \cup \mathcal{V}_{\mathrm{sk}}}((B\sigma \cup ba)^*) \cap \mathrm{Sent}(\mathcal{V} \cup \mathcal{V}(B^*))$. Then we continue with

$$X \overset{\text{Prop. 4}}{\subseteq} \mathrm{PI}^{\mathcal{V} \cup \mathcal{V}' \cup \mathcal{V}_{\mathrm{sk}}}(B^*) \subseteq \mathrm{Enr}(B)$$

Hence $X \cup \{\alpha\}$ is consistent, because $B \circ \alpha$ is consistent. For all β with $B \circ \alpha \models \beta$ and $\beta \in \mathrm{Sent}(\mathcal{V})$ it holds that $B\sigma \cup ba \models \alpha \rightarrow \beta$, hence $X \models \alpha \rightarrow \beta$ and so also $X \cup \{\alpha\} \models \beta$.

8 CONCLUSION

This paper investigated minimality postulates for a particular integration scenario where a receiver agents wants to integrate information stemming from a sender agent. We assumed that the understandings of the symbols by the sender and the receiver are in most cases identical; but if they are used in different meanings, they differ only minimally. Starting off from relevance postulates and inclusion postulates for belief revision operators we defined the postulate of reinterpretation relevance and the postulate of extended inclusion. These specify a global kind of minimal change of the receiver's KB by specifying what is allowed to be eliminated (conflict relevant sentences) from the result and what sentences at most are allowed to be contained in the result.

A novel feature of the postulates is the exploitation of prime implicates. The introduction of prime implicates makes it possible to align one of the assumption for the intended semantic scenario (namely that it is ambiguous use of symbols which causes the conflict) with the fact that contradictions show themselves not on the symbol level but on the sentence level.

The reinterpretation operators recapitulated in this paper can be shown to fulfil the new postulates and as such can be thought of realising a semantic integration which changes the meanings of the receiver's symbols only in a minimal way.

Concerning future work we mention that the postulates (Rel-R) and (Incl-E) are intended to be used as main components for an envisioned representation theorem for predicate logical reinterpretation operators.

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REFERENCES

[1] Carlos Eduardo Alchourrón, Peter Gärdenfors, and David Makinson, 'On the logic of theory change: partial meet contraction and revision functions', *Journal of Symbolic Logic*, **50**, 510–530, (1985).

[2] Carlos Eduardo Alchourrón and David Makinson, 'Hierarchies of regulations and their logic', in *New Studies in Deontic Logic*, ed., R. Hilpinen, 125–148, D. Reidel Publishing, (1981).

[3] Tania Armstrong, Kim Marriott, Peter Schachte, and Harald Søndergaard, 'Two classes of boolean functions for dependency analysis', *Science of Computer Programming*, **31**(1), 3–45, (1998).

[4] Meghyn Bienvenu, 'Prime implicates and prime implicants: From propositional to modal logic', *J. Artif. Intell. Res. (JAIR)*, **36**, 71–128, (2009).

[5] Meghyn Bienvenu, Andreas Herzig, and Guilin Qi, 'Prime implicate-based belief revision operators', in *ECAI*, eds., Malik Ghallab, Constantine D. Spyropoulos, Nikos Fakotakis, and Nikolaos M. Avouris, volume 178, pp. 741–742. IOS Press, (2008).

[6] Samir Chopra, Konstantinos Georgatos, and Rohit Parikh, 'Relevance sensitive non-monotonic inference on belief sequences', *Journal of Applied Non-Classical Logics*, **11**(1–2), 131–150, (2001).

[7] Samir Chopra and Rohit Parikh, 'Relevance sensitive belief structures', in *Annals of Mathematics and Artificial Intelligence*, pp. 259–285, (2000).

[8] James P. Delgrande, 'Horn clause belief change: Contraction functions', in *Principles of Knowledge Representation and Reasoning: Proceedings of the 11th International Conference, KR 2008, Sydney, Australia, September 16-19, 2008*, eds., Gerhard Brewka and Jérôme Lang, pp. 156–165. AAAI Press, (2008).

[9] James P. Delgrande and Torsten Schaub, 'A consistency-based approach for belief change', *Artificial Intelligence*, **151**(1–2), 1–41, (2003).

[10] Dejing Dou, Drew V. McDermott, and Peishen Qi, 'Ontology translation by ontology merging and automated reasoning', in *Proceedings of the EKAW-02 Workshop on Ontologies for Multi-Agent Systems*, pp. 3–18, (2002).

[11] Carola Eschenbach and Özgür L. Özçep, 'Ontology revision based on reinterpretation', *Logic Journal of the IGPL*, **18**(4), 579–616, (2010). First published online August 12, 2009.

[12] Giorgos Flouris, Zhisheng Huang, Jeff Z. Pan, Dimitris Plexousakis, and Holger Wache, 'Inconsistencies, negations and changes in ontologies', in *Proceedings of the 21st National Conference on Artificial Intelligence (AAAI-06)*, pp. 1295–1300, (2006).

[13] Giorgos Flouris, Dimitris Manakanatas, Haridimos Kondylakis, Dimitris Plexousakis, and Grigoris Antoniou, 'Ontology change: classification and survey', *The Knowledge Engineering Review*, **23**(2), 117–152, (2008).

[14] Giorgos Flouris, Dimitris Plexousakis, and Grigoris Antoniou, 'On applying the AGM theory to DLs and OWL', in *Proceedings of the 4th International Semantic Web Conference (ISWC-05)*, pp. 216–231, (2005).

[15] Sven Ove Hansson, 'Changes of disjunctively closed bases', *Journal of Logic, Language and Information*, **2**, 255–284, (1993).

[16] Sven Ove Hansson, 'Reversing the Levi identity', *Journal of Philosophical Logic*, **22**, 637–669, (1993).

[17] Sven Ove Hansson, 'A survey of non-prioritized belief revision', *Erkenntnis*, **50**(2-3), 413–427, (1999).

[18] Sven Ove Hansson, *A Textbook of Belief Dynamics*, Kluwer Academic Publishers, 1999.

[19] David Makinson, 'Propositional relevance through letter-sharing: review and contribution', in *Formal Models of Belief Change in Rational Agents*, (2007).

[20] David Makinson and George Kourousias, 'Parallel interpolation, splitting, and relevance in belief change', *Journal of Symbolic Logic*, **72**, 994–1002, (September 2007).

[21] Thomas Meyer, Kevin Lee, and Richard Booth, 'Knowledge integration for description logics', in *Proceedings of the 20th National Conference on Artificial Intelligence (AAAI-2005)*, pp. 645–650, (2005).

[22] Allan Newell, 'The knowledge level', *Artificial Intelligence*, **18**, 87–127, (1982).

[23] Natalya Fridman Noy, 'Semantic integration: a survey of ontology-based approaches', *SIGMOD Record*, **33**(4), 65–70, (2004).

[24] Özgür L. Özçep, 'Towards principles for ontology integration', in *FOIS*, eds., Carola Eschenbach and Michael Grüninger, volume 183, pp. 137–150. IOS Press, (2008).

[25] Maurice Pagnucco, 'Knowledge compilation for belief change', in *AI 2006: Advances in Artificial Intelligence*, eds., Abdul Sattar and Byeong-ho Kang, volume 4304 of *Lecture Notes in Computer Science*, 90–99, Springer Berlin / Heidelberg, (2006).

[26] Rohit Parikh, 'Beliefs, belief revision, and splitting languages', in *Logic, Language and Computation*, eds., L.S. Moss, J. Ginzburg, and M. de Rijke, volume 2, 266–278, CSLI Publications, (1999).

[27] Guilin Qi and Jianfeng Du, 'Model-based revision operators for terminologies in description logics', in *Proceedings of the 21st international jont conference on Artifical intelligence*, IJCAI'09, pp. 891–897, San Francisco, CA, USA, (2009). Morgan Kaufmann Publishers Inc.

[28] Guilin Qi, Qiu Ji, and Peter Haase, 'A conflict-based operator for mapping revision', in *Proceedings of the 22nd International Workshop on Description Logics (DL-09)*, eds., B. Cuenca Grau, J. Horrocks, B. Motik, and U. Sattler, volume 477 of *CEUR Workshop Proceedings*, (2009).

[29] Marcio M. Ribeiro and Renata Wassermann. Base revision for ontology debugging. Journal of Logic and Computation. Advanced Access, published September 5, 2008, 2008.

[30] Hans Rott, 'Two dogmas of belief revision', *The Journal of Philosophy*, **97**(9), 503–522, (2000).

[31] Zhi Zhuang, Maurice Pagnucco, and Thomas Meyer, 'Implementing iterated belief change via prime implicates', in *AI 2007: Advances in Artificial Intelligence*, eds., Mehmet Orgun and John Thornton, volume 4830 of *Lecture Notes in Computer Science*, 507–518, Springer Berlin / Heidelberg, (2007).