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To cite this version:
Camille Bourgaux. Querying Inconsistent Prioritized Data. DL 2024 - 37th International Workshop on Description Logics, Jun 2024, Bergen, Norway. hal-04591700

HAL Id: hal-04591700
https://hal.science/hal-04591700
Submitted on 29 May 2024

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Querying Inconsistent Prioritized Data

Camille Bourgaux

Abstract
This extended abstract accompanies an invited talk at DL 2024 and presents a summary of some recent results on querying inconsistent prioritized data.

Keywords
inconsistency handling, prioritized data, optimal repairs

Real-world datasets are plagued by data quality issues which may render the data inconsistent w.r.t. a set of constraints, be they given by database dependencies or ontologies. A prominent way to handle such inconsistent data is to use inconsistency-tolerant semantics to obtain meaningful answers to queries [1, 2, 3]. Most of these semantics are based on the notion of a (subset) repair, which is an inclusion-maximal subset of the data that is consistent with the constraints. In many scenarios, this basic notion of repair can be refined by exploiting preference information about facts. Preferred repairs can then be used in place of subset repairs in any repair-based semantics. This paper presents a summary of some recent results [4, 5, 6] on an approach where preferences are given by a binary priority relation between conflicting facts [7].

Formal definitions

A knowledge base (KB) \( \mathcal{K} = (\mathcal{D}, \mathcal{T}) \) consists of a dataset \( \mathcal{D} \) and a logical theory \( \mathcal{T} \): \( \mathcal{D} \) is a finite set of facts, and \( \mathcal{T} \) a finite set of first-order logic (FOL) sentences. Typically, \( \mathcal{T} \) is an ontology, e.g., in description logic, or a set of database constraints, e.g., denial constraints of the form \( \forall \vec{x}. \neg (\alpha_1 \land \ldots \land \alpha_n) \), where each \( \alpha_i \) is a relational or inequality atom. A KB \( \mathcal{K} = (\mathcal{D}, \mathcal{T}) \) is consistent if \( \mathcal{D} \cup \mathcal{T} \) has a model, and inconsistent otherwise (\( \mathcal{K} \models \bot \)). A set of facts \( \mathcal{B} \) is \( \mathcal{T} \)-consistent if \( (\mathcal{B}, \mathcal{T}) \models \bot \); \( \text{Conf}(\mathcal{K}) \) denotes the set of conflicts of \( \mathcal{K} \). A (subset) repair of \( \mathcal{K} = (\mathcal{D}, \mathcal{T}) \) is an inclusion-maximal \( \mathcal{T} \)-consistent subset \( \mathcal{R} \subseteq \mathcal{D} \); \( \text{SRep}(\mathcal{K}) \) denotes the set of repairs of \( \mathcal{K} \). Following [7], we assume that preferences between conflicting facts are available:

Definition 1. A priority relation \( \succ \) for a KB \( \mathcal{K} = (\mathcal{D}, \mathcal{T}) \) is an acyclic binary relation over \( \mathcal{D} \) such that \( \alpha \succ \beta \) implies \( \{\alpha, \beta\} \subseteq \mathcal{C} \) for some \( \mathcal{C} \in \text{Conf}(\mathcal{K}) \). It is total if for all \( \alpha \neq \beta \) such that \( \{\alpha, \beta\} \subseteq \mathcal{C} \) for some \( \mathcal{C} \in \text{Conf}(\mathcal{K}) \), either \( \alpha \succ \beta \) or \( \beta \succ \alpha \). A completion of \( \succ \) is a total priority relation \( \succ' \supseteq \succ \). A prioritized KB \( \mathcal{K}_\succ \) is a KB \( \mathcal{K} = (\mathcal{D}, \mathcal{T}) \) with a priority relation \( \succ \) for \( \mathcal{K} \).

Definition 2 (Optimal repairs). Let \( \mathcal{K}_\succ \) be a prioritized KB with \( \mathcal{K} = (\mathcal{D}, \mathcal{T}) \) and \( \mathcal{R} \in \text{SRep}(\mathcal{K}) \). A Pareto improvement of \( \mathcal{R} \) is a \( \mathcal{T} \)-consistent \( \mathcal{B} \subseteq \mathcal{D} \) such that there is \( \beta \in \mathcal{B} \setminus \mathcal{R} \) with \( \beta \succ \alpha \) for every \( \alpha \in \mathcal{R} \setminus \mathcal{B} \). A global improvement of \( \mathcal{R} \) is a \( \mathcal{T} \)-consistent \( \mathcal{B} \subseteq \mathcal{D} \) such that \( \mathcal{B} \neq \mathcal{R} \) and for every \( \alpha \in \mathcal{R} \setminus \mathcal{B} \), there exists \( \beta \in \mathcal{B} \setminus \mathcal{R} \) such that \( \beta \succ \alpha \). The repair \( \mathcal{R} \) is:
Table 1
Data complexity [7, 4, 5]. Upper bounds hold for conjunctive queries and FOL fragments for which consistency checking and BCQ entailment is in $P$. Lower bounds hold for atomic queries and any fragment that extends DL-Lite$_\text{core}$ or functional dependencies.

<table>
<thead>
<tr>
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<th>Globally-optimal</th>
<th>Pareto-optimal</th>
<th>Completion-optimal</th>
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<tbody>
<tr>
<td>AR, IAR</td>
<td>$\Pi_2^p$-complete</td>
<td>coNP-complete</td>
<td>coNP-complete</td>
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<tr>
<td>Brave</td>
<td>$\Sigma_2^p$-complete</td>
<td>NP-complete</td>
<td>NP-complete</td>
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- Pareto-optimal if there is no Pareto improvement of $\mathcal{R}$;
- globally-optimal if there is no global improvement of $\mathcal{R}$;
- completion-optimal if $\mathcal{R}$ is a globally-optimal repair of $\mathcal{K}_{\succ}$, for some completion $\succ^I$ of $\succ$.

We denote by $P\text{Rep}(K_{\succ})$, $G\text{Rep}(K_{\succ})$ and $C\text{Rep}(K_{\succ})$ the sets of Pareto-, globally- and completion-optimal repairs. It holds that $C\text{Rep}(K_{\succ}) \subseteq G\text{Rep}(K_{\succ}) \subseteq P\text{Rep}(K_{\succ}) \subseteq S\text{Rep}(K)$.

If $\succ$ is induced by assigning scores to facts, then Pareto-, globally- and completion-optimal repairs coincide [8, 9], and also coincide with the $\leq_p$-repairs from [10].

A Boolean conjunctive query (BCQ) $q$ is entailed by a KB $K$ ($K \models q$) if $q$ holds in every model of $K$. Hence, $K \models \bot$ implies that $K \models q$ for every $q$. Meaningful answers can be obtained from inconsistent KBs by using inconsistency-tolerant semantics based on repairs. The AR semantics defines plausible query answers, and is used for consistent query answering in databases [11]. The brave semantics considers all possible answers, while the IAR semantics identifies the most reliable ones. These semantics can be parametrized by the type of repair they consider.

**Definition 3** (Inconsistency-tolerant semantics). Fix $X \in \{S, P, G, C\}$ and consider a prioritized KB $K_{\succ}$ with $K = (D, T)$ and a BCQ $q$. Then $q$ is entailed by $K_{\succ}$ under

- $X$-AR semantics, denoted $K_{\succ} \models^X_{AR} q$, if $(\mathcal{R}, T) \models q$ for every $\mathcal{R} \in X\text{Rep}(K_{\succ})$;
- $X$-brave semantics, denoted $K_{\succ} \models^X_{brave} q$, if $(\mathcal{R}, T) \models q$ for some $\mathcal{R} \in X\text{Rep}(K_{\succ})$;
- $X$-IAR semantics, denoted $K_{\succ} \models^X_{IAR} q$, if $(\mathcal{B}, T) \models q$ where $\mathcal{B} = \bigcap_{\mathcal{R} \in X\text{Rep}(K_{\succ})} \mathcal{R}$.

The semantics are related as follows: $K_{\succ} \models^X_{IAR} q \Rightarrow K_{\succ} \models^X_{AR} q \Rightarrow K_{\succ} \models^X_{brave} q$.

Table 1 gives the data complexity of BCQ entailment under optimal repair-based semantics.\footnote{The lower bound for G-IAR and G-brave with functional dependencies follows from the proof of [7, Theorem 2].}

Note that S-AR entailment is coNP-hard even in very basic settings [12, 13], while S-brave or S-IAR entailment is tractable for DL-Lite ontologies or denial constraints [14].

**Practical SAT-based approaches** [5] The (co)NP complexity results naturally suggest the interest of employing SAT solvers to compute query answers under X-AR, X-brave and X-IAR semantics for $X \in \{P, C\}$, as it has already be done for S-AR [15, 16]. There are several ways of employing SAT encodings to compute answers under (optimal) repair-based semantics, by exploiting different reasoning modes of SAT solvers. The orbits system implements different algorithms and encodings for the case where conflicts are binary. It takes as input the conflicts,
(priority relation, and the potential query answers associated with their causes, where a cause for q is a minimal T-consistent subset C ⊆ D such that (C, T) |= q. Our experimental comparison shows that the choice of algorithm and encoding variant may have huge impact on the computation time. Moreover, while in some cases our results can be used to single out some approaches as more effective, more often there are no clear winner(s). For example, we consider two ways of encoding the absence of a cause, and choosing one instead of the other may make a notable difference, but which one is best depends on the KB and query.

**Connections with abstract argumentation** [4] An argumentation framework (AF) is a pair (Args, ⇝) where Args is a finite set of arguments and ⇝ ⊆ Args × Args is the attack relation: α attacks β if α ⇝ β. The semantics of AFs is based on extensions, which can be seen as coherent sets of arguments. Many notions of extension have been considered, in particular preferred extensions and stable extensions [17]. When these two kinds of extension coincide, the AF is called coherent. We define preference-based set-based argumentation framework (PSETAF), a variant of AF based on collective attacks with a preference relation between arguments. We exhibit a translation of a ‘well-behaved’ set of AICs into a prioritized database and repairs could be explored in the KB setting, e.g., for ontologies with closed predicates [22].

Connections with active integrity constraints [6] In the database setting, active integrity constraints (AICs) state how to resolve constraint violations [20, 21]. A ground AIC is a formula of the form α₁ ∧ · · · ∧ αₙ ∧ ¬β₁ ∧ · · · ∧ ¬βₘ → {A₁, . . . , Aₖ} where the αᵢ, βᵢ are facts and each Aᵢ is an update action of the form −αⱼ for some 1 ≤ j ≤ n or +βⱼ for some 1 ≤ j ≤ m. The semantics of a set of AICs is based on the notion of a repair update, defined as a minimal set U of update actions such that D \ {α | −α ∈ U} ∪ {α | +α ∈ U} satisfies the constraints. Many proposals have been made to select the appropriate repair updates to take into account a set of AICs, such as founded, well-founded, grounded and justified repair updates.

Given a prioritized database (i.e., a prioritized KB such that T is a set of database constraints), we construct a set of ground AICs such that the Pareto-optimal repairs coincide with the repairs obtained by applying founded, grounded and justified repair updates w.r.t. the generated set of AICs. We also exhibit a translation of a ‘well-behaved’ set of AICs into a prioritized database and again relate Pareto-optimal repairs with founded, grounded and justified repair updates. We take this as further evidence that Pareto-optimal repairs are an especially natural notion. These results hold not only for denial constraints but also for universal constraints of the form ∀x(α₁ ∧ . . . ∧ αₙ ∧ ¬β₁ ∧ · · · ∧ ¬βₘ), where repairs can also be obtained by adding facts (while minimizing the symmetric difference with the original database). Such constraints and repairs could be explored in the KB setting, e.g., for ontologies with closed predicates [22].
Acknowledgments

I thank the DL 2024 workshop chairs for inviting me. The work summarized in this extended abstract has been conducted together with Meghyn Bienvenu (CNRS & University of Bordeaux) and supported by the ANR AI Chair INTENDED (ANR-19-CHIA-0014).

References


