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Learning How to Correct a Knowledge Base from the Edit History

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ABSTRACT
The curation of a knowledge base is a crucial but costly task. In this work, we propose to take advantage of the edit history of the knowledge base in order to learn how to correct constraint violations. Our method is based on rule mining, and uses the edits that solved some violations in the past to infer how to solve similar violations in the present. The experimental evaluation of our method on Wikidata shows significant improvements over baselines.

KEYWORDS
knowledge base; history; data cleaning; rule mining; Wikidata

1 INTRODUCTION
Knowledge bases (KBs) play a key role in many applications and lay at the core of the Semantic Web. They contain entities (such as persons, cities, etc.) and statements about them (such as relationships between persons, places of residence, etc.). In this work, we focus on RDFS-style KBs, such as Wikidata [38], YAGO [35] or DBpedia [7]. The data quality of a KB is crucial for its usability. However, it is usually very costly to check the correctness of the data, because KBs can be huge (Wikidata, e.g., contains about 50 millions entities). Moreover, KBs are often built using methods that are error-prone. For instance YAGO and DBpedia are automatically extracted from Wikipedia. Wikidata, for its part, is a collaborative KB that anyone can edit, with more than 18,000 active contributors.

A way of avoiding or at least detecting some of the flaws in the data is to impose constraints on the KB. Such constraints can enforce that some information must be present (e.g., ensuring that every human being has a birth date), or that some statements may not occur (e.g., ensuring that a person is not also a city). Constraints are related to, but different from, ontological rules: A constraint imposes a certain condition, whereas an ontological rule infers certain statements. For example, consider a KB that contains the statement “Spinoza is a human being” without knowing any birth date for Spinoza, and consider a rule “All human beings have a birth date”. If the rule is taken as an ontological rule, then it would just infer that Spinoza has some birth date. If the rule is taken as a constraint, in contrast, the KB would be considered incorrect. Constraints are thus similar in spirit to database integrity constraints.

In practice, constraints often have exceptions. Therefore, it is useful to allow data that does not respect them (in Wikidata, e.g., constraint violations are simply flagged). Nonetheless, by design, most of the constraint violations are not exceptions but actual errors and proposing to repair them is a good starting point when it comes to improving KB quality.

In this paper, we aim at learning how to repair constraint violations. Our goal is to help a KB editor by suggesting how to clean the data locally (providing a solution to a particular constraint violation) or globally (providing rules that can be automatically applied to all constraint violations of a given form once validated by the editor). To do that, we take advantage of the edit history of the KB. We use it to mine correction rules that express how different kinds of constraint violations are usually solved. To the best of our knowledge, this is the first work that builds on past users’ actions to learn local correction strategies.

We start with a brief discussion of works relevant to our problem along three axes: constraints for KBs, KB cleaning, and rule learning.

Constraints. Constraints have long been used in databases and KBs to express rules that the data should follow. Databases typically operate under the closed world assumption, where missing facts are considered to be false. This allows for “completeness” constraints such as tuple generating dependencies. KBs, in contrast, operate under the open world assumption, where missing
facts are not necessarily false. They thus classically have only "correctness" constraints, such as disjointness or functionality axioms (corresponding to special cases of denial constraints and equality generating dependencies in databases).

To express also completeness constraints, several works propose to use description logics, with varying semantics [28, 37]. Another possibility is to use queries that should or should not hold as constraints (see e.g., [24] for methods for writing constraint queries in SPARQL). Other approaches define constraint languages to specify conditions for RDF graph [9] validation, such as SHACL [22] or ShEx [8]. It has been argued in [30] that description logics under the closed world assumption are also suitable for constraint checking in RDF, which can then be implemented with SPARQL queries. In our work, we follow a similar path, using description logic axioms as constraints for RDFS KBs, because it corresponds best to what we observe in current real-world KBs.

Contrary to the above works, we do not aim at expressing constraints, but at repairing their violations. The correction rules we learn for this purpose are similar in spirit to active integrity constraints [11], which specify for each constraint a set of possible repair actions. This type of constraints has recently been applied to description logic KBs as well [32]. Conditioned active integrity constraints add conditions for choosing among the possible actions, and we propose, in a similar spirit, to take into account the context of the constraint violation to correct it. Different from the existing work [11, 32], our goal is to mine correction rules automatically from the edit history of the KB.

Knowledge base cleaning. Several recent approaches have dealt with the interactive cleaning of KBs. The proposed methods detect when a constraint is violated, compute the responsible facts, and work [11, 32], our goal is to mine correction rules automatically from current real-world KBs.

In this paper, we use a vanilla rule mining algorithm inspired by [14]. Our contribution is not the rule mining per se, but the application of rule mining to the edit history of a KB in order to mine correction rules. This avenue has, to the best of our knowledge, never been investigated.

3 PRELIMINARIES

In this work, we use description logics (DL) [4] as KB language and as constraint language, because they are the foundation of the Semantic Web standard OWL [16].

Syntax. We assume a set $N_C$ of concept names (unary predicates, also called classes), a set $N_R$ of role names (binary predicates, also called properties), and a set $N_I$ of individuals (also called constants). An ABox (dataset) is a set of concept or role assertions of the form $A(a)$ or $R(a,b)$, where $A \in N_C, R \in N_R, a, b \in N_I$. A TBox (ontology) is a set of axioms whose form depends on the DL $\mathcal{L}$ in question, and expresses relationships between concepts and roles (e.g., concept or role hierarchies, role domains and ranges...). A knowledge base (KB) $\mathcal{K} = \mathcal{T} \cup \mathcal{A}$ is the union of an ABox $\mathcal{A}$ and a TBox $\mathcal{T}$.

In this work, we assume that $\mathcal{T}$ is a flat QL TBox [23], i.e., that $\mathcal{L}$ differs from the standard RDF Schema (RDFS) [17] only by allowing inverse roles in role inclusions. More precisely, $\mathcal{T}$ can contain concept inclusions of the form $A_1 \sqsubseteq A_2$ (subclass), $\exists P \sqsubseteq A$ (domain or range), and role inclusions $P_1 \sqsubseteq P_2$ (subproperty), where $A_i \in N_C$ and $P_i \in N_R$.

A KB can also be written as a set of RDF triples $(s, p, o)$ where $s$ is the subject, $p$ is the property, and $o$ the object, using special properties to translate concept membership and relationships between concepts and roles [29]. A concept assertion $A(a)$ is written as $(a, rdf: type, A)$, and a role assertion $R(a,b)$ as $(a, R, b)$. Flat QL TBox axioms can also be represented by single triples. For example, $A_1 \sqsubseteq A_2$ is written as $(A_1, rdfs: subClassOf, A_2)$ and $\exists R \sqsubseteq A$ is written as $(R, rdfs: range, A)$.

Semantics. We recall the standard semantics of DL KBs. An interpretation has the form $I = (\Delta^I, \cdot^I)$, where $\Delta^I$ is a non-empty set and $\cdot^I$ is a function that injectively maps each $a \in N_I$ to $a^I \in \Delta^I$ (unique name assumption). $\mathcal{T}$ to $\Delta^I$, each $A \in N_C$ to $A^I \subseteq \Delta^I$, and each $R \in N_R$ to $R^I \subseteq \Delta^I \times \Delta^I$. The function $\cdot^I$ is straightforwardly extended to general concepts and roles, e.g. $(\neg B)^I = \Delta^I \setminus B^I$, $(R^{-1})^I = \{(c,d) | (d,c) \in R^I\}$, $(\cdot a_1, \ldots, a_n)^I = \{a^I_1, \ldots, a^I_n\}$, $(\exists P \cdot B)^I = \{c | \exists d : (c,d) \in P^I, d \in B^I\}$, $(B_1 \cap B_2)^I = B_1^I \cap B_2^I$, $(B_1 \cup B_2)^I = B_1^I \cup B_2^I$. An interpretation $I$ satisfies an inclusion $G \sqsubseteq H$, if $G^I \subseteq H^I$; it satisfies an axiom (func $P$) if $P^I$ is functional; it satisfies an axiom (trans $P$) if $P^I$ is transitive; and it satisfies $A(a)$ (resp. $R(a,b)$), if $a^I \in A^I$ (resp. $(a^I, b^I) \in R^I$). We write $I \models a$ if $I$ satisfies the DL axiom $a$.

An interpretation $I$ is a model of $\mathcal{K} = \mathcal{T} \cup \mathcal{A}$ if $\mathcal{I}$ satisfies all axioms in $\mathcal{K}$. A KB $\mathcal{K}$ entails a DL axiom $a$ if $I \models a$ for every model $I$ of $\mathcal{K}$.

Queries. A conjunctive query (CQ) takes the form $q(\vec{x}) = \exists \vec{y} \phi(\vec{x}, \vec{y})$, where $\phi$ is a conjunction of atoms of the form $A(t)$ or $R(t, t')$ or of equalities $t = t'$, where $t, t'$ are individual names or variables from
We denote by $\bigcup \mathcal{L}$ a Boolean CQ (BCQ). A BCQ $q$ is satisfied by an interpretation $I$, written $I \models q$, if there is a homomorphism $\pi$ mapping the variables and individual names of $q$ into $\Delta$ such that: $\pi(a) = a^I$ for every $a \in N_1$, $\pi(t) = a^I$ for every concept atom $A(t) \in \Delta$ with $\psi(\pi(t), \pi(t')) \in R_I^+$ for every role atom $R(t, t') \in \psi$, and $\pi(t) = \pi(t')$ for every $t = t'$ in $\psi$. We also consider as BCQs the queries true and false which are respectively always and never satisfied by an interpretation. A BCQ $q$ is entailed from $\mathcal{K}$, written $\mathcal{K} \models q$, iff $q$ is satisfied by every model of $\mathcal{K}$. A tuple of constants $\bar{a}$ is a (partial) answer to a CQ $q(\bar{x})$ if $\mathcal{K} \models q(\bar{a})$ where $q(\bar{a})$ is the BCQ obtained by replacing the variables from $\bar{x}$ by the constants $\bar{a}$. We denote by $\text{answ}(q(\bar{x}), \mathcal{K})$ the set of answers of $q(\bar{x})$ over $\mathcal{K}$. A union of CQs (UCQ) is a disjunction of CQs and has as answers the union of the answers of the CQs it contains.

**Canonical model.** It is well-known that a flat QL KB $\mathcal{K}$ has a canonical model $I_\mathcal{K}$ such that for every BCQ $q$, $\mathcal{K} \models q$ iff $I_\mathcal{K} \models q$. The domain of $I_\mathcal{K}$ is the set of individual names that occur in $\mathcal{K}$ and $A^{I_\mathcal{K}} = \{a \mid A \models B(a), T \models B \subseteq A\}$ for every $A \in N_2$ and $R^{I_\mathcal{K}} = \{(a, b) \mid A \models P(a, b), T \models P \subseteq R\}$ for every $R \in N_2$.

**4 CONSTRAINTS**

This section defines the constraints that can be imposed on a KB, and relates the problem of checking that a KB complies with these constraints to CQ answering over this KB.

**Defining constraints.** In this work, we consider two types of constraints: consistency constraints (which express that some statements are contradictory), and completeness constraints (which impose that certain statements should hold in the KB as soon as some others do). While violations of consistency constraints can only be solved by removing statements, those of completeness constraints can only be solved by adding statements.

**Definition 1 (Constraint):** Constraints are built from complex concepts and roles defined by the following grammar rules:

$$P := R | R^+$$

$$B := \top | A | B \cap B | B \cup B | \exists P \cdot \{a_1, \ldots, a_n\} | \exists P \cdot B$$

where $R \in N_R$, $A \in N_C$, $a_1, \ldots, a_n \in N_I$.

A consistency constraint is a concept inclusion of the form $B_1 \subseteq \neg B_2$ or of the form $B \subseteq \{a_1, \ldots, a_n\}$, a role inclusion of the form $P_1 \subseteq \neg P_2$, or a functionality axiom of the form $(fun P)$. A completeness constraint is a concept inclusion of the form $B_1 \subseteq B_2$, a role inclusion of the form $P_1 \subseteq P_2$, or a transitivity axiom of the form $(trans P)$.

This definition of constraints covers the "constraining" versions of the majority of the most popular DL axioms used on the Web of Data according to the ranking done by [15].

We assume without loss of generality that concepts of the form $B_1 \cup B_2$ or $\{a_1, \ldots, a_n\}$ with $n > 1$ appear only on the right side of inclusions, and not at all in negative inclusions of the form $B_1 \subseteq \neg B_2$. For example, we assume that $\exists P \cdot (B_1 \cup B_2) \subseteq C$ is rewritten as $\exists P \cdot B_1 \subseteq C$, $\exists P \cdot B_2 \subseteq C$, and $B \subseteq \neg \exists P \cdot \{a_1, \ldots, a_n\}$ is rewritten as $B \subseteq \neg \exists P \cdot \{a_1, \ldots, a_n\}$, $B \subseteq \neg \exists P \cdot \{a_1, \ldots, a_n\}$. As usual, we abbreviate $\exists P \cdot \top$ as $P$.

**Example 1:** As a running example, we consider the following KB $\mathcal{K} = \mathcal{T} \cup \mathcal{A}$ and set of constraints $C$ inspired from Wikidata. Our TBox $\mathcal{T}$ expresses that human beings and deities are persons. Our ABox $\mathcal{A}$ provides information on several individuals. Our constraints $C$ state that there are three possible genders (consistency constraint), that those who have a mother or are a mother must be persons or animals, that a mother must have gender female, and that if $a$ has mother $b$, then $b$ must have child a (completeness constraints).

$$\mathcal{T} = \{ \text{Human} \sqsubseteq \text{Person}, \text{Deity} \sqsubseteq \text{Person} \}$$

$$\mathcal{A} = \{ \text{Deity}(Zeus), \text{Deity}(Rhea), \text{hasGender}(Zeus, \text{masculine}), \text{hasGender}(Rhea, \text{female}), \text{hasMother}(Zeus, \text{Rhea}), \text{hasChild}(Rhea, \text{Zeus}), \text{Human}(\text{Spinoza}), \text{hasMother}(\text{Spinoza}, \text{Marques}) \}$$

$$C = \{ \Gamma_0 = \exists \text{hasGender} \subseteq \{ \text{male}, \text{female}, \text{nonbinary} \}, \Gamma_1 = \exists \text{hasMother} \sqsubseteq \text{Person} \sqcup \text{Animal}, \Gamma_2 = \exists \text{hasMother} \subseteq \text{Person} \sqcup \text{Animal}, \Gamma_3 = \exists \text{hasMother} \subseteq \exists \text{hasGender} \cdot \{\text{female}\}, \Gamma_4 = \exists \text{hasMother} \subseteq \exists \text{hasChild} \}$$

We say that a KB $\mathcal{K}$ satisfies a constraint $\Gamma \in C$ if $I_\mathcal{K} \models \Gamma$, where $I_\mathcal{K}$ is the canonical model of $\mathcal{K}$. Otherwise, $\mathcal{K}$ violates $\Gamma$.

**Example 2:** In our running example, the KB $\mathcal{K}$ satisfies $\Gamma_1$ since $\exists \text{hasMother}^{I_\mathcal{K}} = \{ \text{Zeus}, \text{Spinoza} \}$ and $I_\mathcal{K} \models \text{Person}(\text{Zeus})$ and $I_\mathcal{K} \models \text{Person}(\text{Spinoza})$. However, it violates $\Gamma_2$ because $I_\mathcal{K} \not\models \text{Person} (\text{Marques}) \sqcup \text{Animal} (\text{Marques})$ while Marques $\in \exists \text{hasMother}^{I_\mathcal{K}}$. It violates $\Gamma_3$ and $\Gamma_4$ for similar reasons. Finally, $\{ \text{hasGender}(\text{Zeus, masculine}), \Gamma_0 \}$ has no model because of the unique name assumption (which enforces that the interpretation of masculine differs from those of male, female and nonbinary). Hence, $I_\mathcal{K}$ cannot be a model of $\Gamma_3$. Thus, $\mathcal{K}$ violates $\Gamma_0$.

Note the semantic difference between the constraints and the axioms of the TBox: The axiom (Human $\sqsubseteq$ Person) in the TBox makes every human an answer to the query asking for persons. In contrast, if we had put the axiom in the set of constraints, it would have required all human beings in the KB to be explicitly marked as persons. As another example, consider the axiom (func hasBirthdate) (which says that everyone can have at most one birth date). If this axiom appears in the TBox, it renders the KB inconsistent whenever a person is given two distinct dates of birth. This has severe consequences on the reasoning capabilities, since everything is entailed from an inconsistent KB. If this axiom is in the set of constraints, in contrast, then distinct dates of birth lead only to the violation of the constraint. This gives us relevant information without having any impact on the usability of the KB.

**Checking constraints.** We show that our setting allows us to check constraint satisfaction via CQ answering. For this purpose, we use a function $\pi$, which maps each constraint $\Gamma \in C$ to a rule of the form $\exists \varphi(x, y) \rightarrow \exists \varphi'(x, z)$, which function is defined recursively as shown in Table 1. The left side of the rule is called the body and its right side the head.

**Example 3:** In our running example, we obtain the following rules:

$$\Gamma_0(x) : \exists y \text{hasGender}(y, x) \rightarrow x = \text{male} \lor x = \text{female} \lor x = \text{nonbinary}$$

$$\Gamma_1(x) : \exists y \text{hasMother}(x, y) \rightarrow \text{Person}(x) \lor \text{Animal}(x)$$

$$\Gamma_2(x) : \exists y \text{hasMother}(x, y) \rightarrow \text{Person}(x) \lor \text{Animal}(x)$$

$$\Gamma_3(x) : \exists y \text{hasMother}(x, y) \rightarrow \exists z (\text{hasGender}(x, z) \land z = \text{female})$$

$$\Gamma_4(x, y) : \text{hasMother}(x, y) \rightarrow \text{hasChild}(y, x)$$
Table 1: Translation of DL axioms into rules. Variables that appear in the right column and not in the left one are fresh.

<table>
<thead>
<tr>
<th>Rule</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi(T, x) )</td>
<td>true</td>
</tr>
<tr>
<td>( \pi(A(x)) )</td>
<td>( A(x) )</td>
</tr>
<tr>
<td>( \pi([a_1, \ldots, a_n], x) )</td>
<td>( x = a_1 \lor \cdots \lor x = a_n )</td>
</tr>
<tr>
<td>( \pi(R(x, y)) )</td>
<td>( R(x, y) )</td>
</tr>
<tr>
<td>( \pi(B_1 \sqcap B_2, x) )</td>
<td>( \pi(B_1, x) \land \pi(B_2, x) )</td>
</tr>
<tr>
<td>( \pi(\exists P.B, x) )</td>
<td>( \exists y(\pi(P, x, y) \land \pi(B, x)) )</td>
</tr>
<tr>
<td>( \pi(B \subseteq C) )</td>
<td>( \pi(B, x) \rightarrow \pi(C, x) )</td>
</tr>
<tr>
<td>( \pi(P \subseteq \neg Q) )</td>
<td>( \pi(P, x, y) \land \pi(Q, x, y) \rightarrow false )</td>
</tr>
<tr>
<td>( \pi(func P) )</td>
<td>( \pi(P, x, y) \land \pi(P, x, z) \rightarrow y = z )</td>
</tr>
</tbody>
</table>

Definition 2 (Constraint violation): A violation of a constraint \( \Gamma(\bar{x}) \) in \( \mathcal{K} \) is a minimal subset \( \mathcal{V} \subseteq \mathcal{K} \) such that there exists \( \bar{a} \) such that \( \mathcal{V} \) violates \( \Gamma(\bar{a}) \) and \( \mathcal{K} \) violates \( \Gamma(\bar{a}) \). We denote by \( \text{Violations}(\mathcal{K}, \Gamma(\bar{x})) \) the set of violations of \( \Gamma(\bar{x}) \).

In this definition, the requirement that \( \mathcal{K} \) violates \( \Gamma(\bar{a}) \) may seem superfluous. Yet, if \( \Gamma \) is a completeness constraint, it may be the case that some \( \mathcal{V} \subseteq \mathcal{K} \) violates \( \Gamma(\bar{a}) \), while \( \mathcal{K} \) satisfies it.

Example 4: In our running example, it is easy to see that the sub-set \( \mathcal{V}_0 = \{ \text{hasGender(Zeus, masculine)} \} \) is a violation of \( \Gamma_0 \). Consider now \( \mathcal{V} = \{ \text{hasMother(Spinoza, Marques)} \} \). \( \mathcal{V} \) is a violation of \( \Gamma_2, \Gamma_3 \) and \( \Gamma_4 \). Indeed, it violates \( \Gamma_2(\text{Marques}) \), \( \Gamma_3(\text{Marques}) \), and \( \Gamma_4(\text{Spinoza, Marques}) \) and \( \mathcal{K} \) does not satisfy any of these constraint instances. However, even if \( \mathcal{V} \) violates \( \Gamma_1(\text{Spinoza}) \), \( \mathcal{V} \) is not a violation of \( \Gamma_1 \) because \( \{ \text{Human(Spinoza), Human \sqsubseteq Person} \} \subseteq \mathcal{K} \) satisfies the head of \( \Gamma_1(\text{Spinoza}) \).

If a constraint instance \( \Gamma(\bar{a}) \) is violated, \( \bar{a} \in \text{answers}(h(\bar{x}), \mathcal{K}) \) and \( \bar{a} \notin \text{answers}(b(\bar{x}), \mathcal{K}) \), so its violations are the minimal subsets of \( \mathcal{K} \) responsible for \( \bar{a} \in \text{answers}(b(\bar{x}), \mathcal{K}) \). The next proposition relates constraint violations and justifications. A justification (also known as an explanation, axiom pinpointing, or MinAs) for the entailment of a BCQ is a minimal subset of the KB that entails the BCQ [21, 34].

Proposition 2: If \( \mathcal{K} \) violates \( \Gamma(\bar{a}) : b(\bar{a}) \rightarrow h(\bar{a}) \), a subset \( \mathcal{V} \subseteq \mathcal{K} \) is a violation of \( \Gamma(\bar{a}) \) iff \( \mathcal{V} \) is a justification of \( \mathcal{K} \models b(\bar{a}) \).

5 CORRECTIONS

We now turn to correcting constraint violations.

Solutions. We will make use of atomic modifications of the KB to define solutions to constraint violations.

Definition 3 (Atomic modification): An atomic modification of a KB \( \mathcal{K} \) is a pair \( m = (\mathcal{M}^+, \mathcal{M}^-) \) of two sets of assertions or \( \mathcal{L} \)-axioms that takes one of the following forms:

Addition: \( m = \{ ((s, p, o), \theta) \} \), where \( (s, p, o) \notin \mathcal{K} \)

Deletion: \( m = \{ (\emptyset, ((s, p, o))) \} \), where \( (s, p, o) \in \mathcal{K} \)

Replacement: \( m = \{ ((s, p, o)), \{ (s', p', o') \} \} \), where \( (s, p, o) \notin \mathcal{K} \), \( (s', p', o') \in \mathcal{K} \), and \( (s, p, o) \) differs from \( (s', p', o') \) in exactly one component.

Thus, an atomic modification consists of two sets \( \mathcal{M}^+ \) and \( \mathcal{M}^- \), each of which is either the empty set or a singleton set. \( \mathcal{M}^+ \) will be added to the KB, and \( \mathcal{M}^- \) will be removed from the KB. Since the sets contain at most one triple, we slightly abuse the notation and identify the singletons with their elements (e.g., we will denote the addition of \( (s, p, o) \) simply by \( (s, p, o, \theta) \)). A replacement is equivalent to a sequence of a deletion and an addition. We chose to keep it as an atomic modification because it corresponds to common knowledge base curation tasks, such as correcting an erroneous object for a given subject and predicate, or fixing a predicate misuse. Atomic modifications can be used to solve a constraint violation, as follows:

Definition 4 (Solution): A solution to a violation \( \mathcal{V} \) of a constraint instance \( \Gamma(\bar{a}) \) in \( \mathcal{K} \) is an atomic modification \( (\mathcal{M}^+, \mathcal{M}^-) \) such that there exists \( \mathcal{K}' \subseteq \mathcal{K} \) such that \( \mathcal{V} \cup \mathcal{K}' \cup \mathcal{M}^+ \setminus \mathcal{M}^- \) satisfies \( \Gamma(\bar{a}) \). We call \( (\mathcal{M}^+, \mathcal{M}^-) \) a solution to \( \mathcal{V} \) for \( \Gamma(\bar{a}) \) in \( \mathcal{K} \).

Note that \( \Gamma(\bar{a}) \) can still be violated in \( (\mathcal{K} \cup \mathcal{M}^+) \setminus \mathcal{M}^- \) if \( \mathcal{K} \) contains other violations of \( \Gamma(\bar{a}) \) for which \( (\mathcal{M}^+, \mathcal{M}^-) \) is not a solution. For example, if \( \Gamma(\bar{a}) : \exists x \, r(x, a) \land A(a) \rightarrow false \), and \( \mathcal{K} = \{ r(a, b), r(a, c), A(a) \} \), the deletion of \( r(a, b) \) is a solution to the violation \( \{ r(a, b), A(a) \} \), but \( \{ r(a, c), A(a) \} \) still violates \( \Gamma(a) \).

Note also that every constraint violation has at least one solution, which consists of the deletion of any of its elements. Solutions may also be additions or replacements, as in the following example:

Example 5: In our running example, the deletion (\( \emptyset \), hasGender (Zeus, masculine)) and the replacement (hasGender(Zeus, male),
We thus consider only those past corrections that would have been given in the past. The edit history allows us to pinpoint how constraint violations are solved. Good solutions. Our goal is to find “good” solutions to constraint violations, i.e., solutions that make the KB as close to the real world as possible. The basic requirement for a “good” solution is that it deletes only erroneous facts, and that it adds only true facts. We also prefer replacements over deletions as long as they fulfill this condition. For instance, in our running example, the replacement hasGender(Zeus, male), hasGender(Zeus, masculine)) is better than the deletion (∅, hasGender(Zeus, masculine)), because it corrects erroneous information instead of simply erasing it.

In some cases, there may be no “good” solution that consists of a single atomic modification. Consider for example a completeness constraint of the form A ⊆ P : B violated by (A, a). If A(a) is true, we should actually add both P(a, b) and B(b) for some b. We choose to define solutions as atomic modifications nevertheless to simplify the problem by reducing the size of possible solutions. This is a limitation of our approach since we will not be able to learn solutions that are not atomic. However, we will still be able to learn to add b(b) to solve the aforementioned constraint violation in the case where P(a, b) is already present.

The main difficulty in finding good solutions to constraint violations is that we do not have access to an oracle that knows the validity of all facts. This is the problem that all KB cleaning approaches face (cf. Section 2). Our idea is to exploit the history of the KB modifications to learn how to correct constraint violations.

Definition 5 (Edit history): The edit history of a KB is a sequence of KBs K0 = (K0 ∪ T0, M0) such that K1 = (K0 ∪ M1, M1) where (M1, M1) is an atomic modification.

The edit history allows us to pinpoint how constraint violations have been corrected in the past. In order to avoid learning from vandalism or mistakes, we consider only those corrections that have not been reversed:

Definition 6 (Past correction): A past correction is a solution (M∗, M−) to a violation V of a constraint instance Γ(α) in K such that there exist B and D such that the current KB Kp = (K ∪ B) \ D with M∗ ⊆ B, M− ⊆ D, M∗ ∩ D = ∅, M− ∩ B = ∅.

Intuitively, (B, D) corresponds to the sequence of additions and deletions that leads from K0 to the current state of the KB Kp, that contains the solution, and that does not “undo” it.

Relevant past corrections. During the history of a KB, users can change not just the assertions of the KB, but also the TBox. However, the TBox is typically much smaller and more stable than the ABox. Therefore, the edit history of the TBox is not a rich ground for correction rule mining. Moreover, we are interested in learning solutions that correct constraint violations in the current KB Kp, We thus consider only those past corrections that would have been corrections also under the current TBox. For example, assume that the TBox contained C ⊆ B. Assume that C(a) was added to correct a violation of the constraint A ⊆ B. If, in the meantime, the inclusion C ⊆ B has been removed, we do not want to learn from this past correction. The following definition formalizes these requirements.

Definition 7 (Relevant Past Correction): A relevant past correction (M∗, M−) to a violation V of a constraint instance Γ(α) in K is a past correction such that (i) M∗ ∩ M− contains only assertions, and (ii) V \ A0 \ T1 contains a violation V′ of Γ(α) such that (M∗, M−) is also a solution to V′ in A0 ∪ T1.

We will now see how we can use the relevant past corrections to mine correction rules.

6 FROM HISTORY TO CORRECTION RULES

In this section, we propose an approach based on rule mining to learn correction rules for building solutions to constraint violations.

6.1 Extraction of the Relevant Past Corrections

Algorithm 1 constructs the set of relevant past corrections from the KB history. It consists of three main steps. First, it constructs patterns to spot KB modifications that could be part of a relevant past correction. Then it uses these patterns to extract atomic modifications that solved some violation in the past. Finally, the relevant past corrections are obtained by pruning those that have been reversed.

Algorithm 1 Construction of PCDataset

Input: set of constraints C, current TBox Tp, history (Ki)i∈[0:p]
Output: set of relevant past corrections PCDataset

// Construct correction seed patterns
for all Γ ∈ C such that Γ(α) : b(α) → h(α) do
    Patterns(Γ) := {(ψ, A(ψ)) | A(ψ) ∈ b′(ψ), b′(ψ) rewrite(b(ψ), Tp)}
if Γ is a completeness constraint then
    Patterns(Γ) := {(ψ, A(ψ)) | A(ψ) ∈ h′(ψ),
        h′(ψ) rewrite(h(ψ), Tp)}
// Extract past corrections
for 0 ≤ i ≤ p - 1 do
    if (M∗i, M−i) such that Ki+1 = (Ki ∪ M∗i) \ M−i matches
        some pattern in Patterns(Γ) then
        PCDataset := {{(M∗i, M−i), Γ(α), V, i} | V ∈ Violations(Ki, Γ(α)) \ Violations(Ki+1, Γ(α))}
// Remove reversed past corrections
for {(M∗i, M−i), Γ(α), V, i} ∈ PCDataset do
    if M∗i ∉ Ki or M−i ∉ Ki+1 then
        PCDataset := {{(M∗i, M−i), Γ(α), V, i}}

Let us explain our algorithm with our running example. Consider the constraint I0(x) : ∃y hasGender(y, x) → x = male ∨ x = female ∨ x = nonbinary. Assume that (Zeus, hasGender, masculine) was added between K1 and K2, but then replaced by (Zeus, hasGender, male) between K100 and K101.

The first goal of the algorithm is to find out that the removal of (Zeus, hasGender, masculine) between K100 and K101 (as part of the replacement) may be part of a relevant past correction. We call this deletion a correction seed. Formally, a correction seed is a deletion (∅, M−) or an addition (M∗, ∅) such that (i) there exists 0 ≤ i ≤ p - 1 such that Ki+1 = (Ki ∪ M∗i) \ M−i with M∗i = M−i.
We collect the patterns for the constraint \( \Gamma \) which is not in violations for all constraints on all KB versions has the advantage of significantly reducing the search space. To find such correction seeds efficiently, the first step of the algorithm precomputes for each constraint a set of atomic modification patterns that the possible correction seeds would match. In the example there would be only one pattern: the deletion pattern \(_b(\_?, \text{hasGender}, \_?)\) which could have been anything so that it matches both the deletion of \(_b(\_?, \text{hasGender}, \_?)\) and its replacements. So we only consider past corrections that involve assertions, and want them to be relevant for the current TBox, computing the correction seed patterns can be done via query rewriting of the CQs in the body \( h(\bar{x}) \) and the head \( h(\bar{z}) \) of the constraint w.r.t. \( \mathcal{T}_p \). Indeed, if \( T \) is a flat QL TBox, any CQ \( q(\bar{x}) \) can be rewritten w.r.t. \( T \) into a UCQ \( q'(\bar{x}) \) such that for every ABox \( \mathcal{A} \), answering \( q(\bar{x}) \) over \( T \cup \mathcal{A} \) amounts to answering \( q'(\bar{x}) \) over \( \mathcal{A} \) [23]. Each atom that occurs in the rewriting of the body of a constraint corresponds to a deletion pattern, and each atom that occurs in the rewriting of the head of a completeness constraint corresponds to an addition pattern. We collect the patterns for the constraint \( \Gamma \) in the set Patterns(\( \Gamma \)). Note that it is not possible to solve a consistency constraint with an addition, which is why such constraints have only deletion patterns.

The second step of the algorithm verifies, for each correction seed, whether it solved some constraint violation in the past – i.e., whether \( \mathcal{K}_i \) contains some violations of some constraint instances that are not in \( \mathcal{K}_{i+1} \). If so, the modification between \( \mathcal{K}_i \) and \( \mathcal{K}_{i+1} \) is a solution that solved these violations in \( \mathcal{K}_i \). In the example we would have found the violation \( \{\langle \text{Zeus}, \text{hasGender}, \text{male} \rangle \} \) of \( \mathcal{I}_0(\text{male}) \) in \( \mathcal{K}_{100} \), which is not in \( \mathcal{K}_{101} \). So we would have extracted that \( \{\langle \text{Zeus}, \text{hasGender}, \text{male} \rangle, \langle \text{Zeus}, \text{hasGender}, \text{masculine} \rangle \} \) is a solution that solved the violation \( \{\langle \text{Zeus}, \text{hasGender}, \text{male} \rangle \} \) of \( \mathcal{I}_0(\text{male}) \) in \( \mathcal{K}_{100} \). We store this information as a tuple in the relevant past corrections dataset (the PCDataset), as shown in Table 2. Finding the constraint instances violated in \( \mathcal{K}_i \) or \( \mathcal{K}_{i+1} \) is done via CQ answering (Proposition 1), and computing their violations amounts to computing BCQ justifications (Proposition 2).

The final step of the algorithm removes corrections that have been reversed. The result is thus the set of relevant past corrections.

### 6.2 Correction Rule Mining

**Definition 8 (Correction rule):** A correction rule is of the form:

\[
r := [\Gamma(\bar{x})] : E(\bar{x}, \bar{y}, \bar{z}) \rightarrow (M^+(\bar{x}, \bar{y}), M^-(\bar{x}, \bar{y})),
\]

where

- \( \Gamma(\bar{x}) \) is a constraint that can be partially instantiated, i.e., some of its variables have been replaced by constants,
- \( (M^+(\bar{x}, \bar{y}), M^-(\bar{x}, \bar{y})) \) is a pair of sets of at most one triple,
- \( E(\bar{x}, \bar{y}, \bar{z}) \) is a set of atoms called the context of the violation such that \( M^-(\bar{x}, \bar{y}) \subseteq E(\bar{x}, \bar{y}, \bar{z}) \), and both \( (M^+(\bar{x}, \bar{y}), M^-(\bar{x}, \bar{y})) \) and \( E(\bar{x}, \bar{y}, \bar{z}) \) are built from \( N_C \cup N_R \cup \{\text{rdf:} \text{type}\} \cup N_1 \cup \bar{x} \cup \bar{y} \cup \bar{z} \).

A correction rule can be applied to a KB \( \mathcal{K} \) when there exist tuples of constants \( \bar{a}, \bar{b} \) such that \( \mathcal{K} \) violates \( \Gamma(\bar{a}) \) (recall that this can be decided via CQ answering by Proposition 1) and \( \mathcal{K} \models \exists \exists E(x, \bar{y}, \bar{z}) \). The result of the rule application is then \( (M^+(\bar{a}, \bar{b}), M^-(\bar{a}, \bar{b})) \).

Note that while the variables from \( E(\bar{x}, \bar{y}, \bar{z}) \) that do not appear in \( \Gamma(\bar{x}) \) or in the head of \( r \) can be existentially quantified, those that occur in the head of \( r \) have to be free: they have to be mapped to individuals occurring in the KB in order to construct the result.

**Example 6:** In our running example, we would like to learn the following correction rules:

\[
r_1 := [\Gamma(\text{male})] : \{\text{hasGender}(y, \text{male})\} \rightarrow (\text{hasGender}(y, \text{male}), \text{hasGender}(y, \text{masculine}))
\]

\[
r_2 := [\Gamma(\text{male})] : \{\text{hasMother}(y, x), \text{Human}(y)\} \rightarrow (\text{Human}(x), \emptyset)
\]

The context of the second rule says that if \( x \) is the mother of a human, then \( x \) must also be a human. The rule obtained by replacing Human by Animal would express how to solve a violation of \( \Gamma_2 \) in the context where \( y \) is an animal.

**Mining correction rules.** We mine correction rules with Algorithm 2. This algorithm is an adaptation of the algorithm in [13, 14] to our context, where we learn rules not from a KB but from the PCDataset and the KB history. We first adapt the definitions of the confidence and support from [13, 14] to our case. The support of the body of a correction rule \( r \) for a constraint \( \Gamma \) is the number of violations of \( \Gamma \) stored in the PCDataset that could have been corrected by applying \( r \). Such violations are associated with an instance \( \Gamma(\bar{a}) \) of the partially instantiated \( \Gamma(\bar{x}) \) that appears in \( \mathcal{K}_i \) with an index \( i \) such that \( \mathcal{K}_i \models \exists \exists E(\bar{a}, \bar{b}, \bar{z}) \) for some \( \bar{b} \). These two conditions imply that \( r \) could be applied to the KB \( \mathcal{K}_i \). Moreover, we need to check that the result of applying \( r \) to \( \mathcal{K}_i \) actually gives a solution to \( \mathcal{V} \). For example, consider the case where PCDataset contains both \( \{(\emptyset, \text{R}(a, b)), \text{R}(a, b), A(a), i\} \) and \( \{(\emptyset, \text{R}(a, c)), \text{R}(a, c), A(a), j\} \) for \( \text{R}(a, c) \rightarrow (\emptyset, \text{R}(a, c)) \). This implies that \( \text{R}(a, x) \rightarrow (\emptyset, \text{R}(a, x)) \) for both the second one counts for the support of the body of \( \text{R}(a, c) \rightarrow (\emptyset, \text{R}(a, c)) \), even in the case where \( \mathcal{K}_i \models \text{R}(a, c) \). Formally, \( \text{sup}_{\text{Body}}(r) = |B_{\text{Sup}}(r)| \) where

\[
B_{\text{Sup}} = \{\mathcal{V} \mid \exists \exists E(\bar{a}, \bar{b}, \bar{z}), \mathcal{K}_i \models \exists \exists E(\bar{a}, \bar{b}, \bar{z}) \}
\]

and the result of the application of \( r \) to \( \mathcal{K}_i \) is a solution to \( \mathcal{V} \).

<table>
<thead>
<tr>
<th>Relevant past correction</th>
<th>Constraint instance</th>
<th>Violation</th>
<th>KB index</th>
</tr>
</thead>
<tbody>
<tr>
<td>{\langle \text{Zeus}, \text{hasGender}, \text{male} \rangle }, {\langle \text{Zeus}, \text{hasGender}, \text{masculine} \rangle }</td>
<td>\text{I}_0(\text{male})</td>
<td>{\langle \text{Zeus}, \text{hasGender}, \text{masculine} \rangle }</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 2: Dataset PCDataset of relevant past corrections extracted for our running example.
The support of the rule \( r \) measures when the past correction is exactly the result of the application of the rule in the cases where it could be applied. Formally, \( \text{sup}_{\text{rule}}(r) = |\text{RSup}| \), where

\[
\text{RSup} = \{ V \mid ((M^+ (\bar{a}, \bar{b})), M^-(\bar{a}, \bar{b})), \Gamma(\bar{a}), \forall, i) \in \text{PCDataset}, \text{ and } \mathcal{K}_i \models \exists E(\bar{a}, \bar{b}, \bar{z}) \}.
\]

Finally, the confidence of a correction rule \( r \) is \( \text{conf}(r) = \frac{\text{sup}_{\text{rule}}(r)}{\text{sup}_{\text{rule}}(\Gamma)} \).

**Algorithm 2 Correction rule mining**

**Input:** PCDataset, \((\mathcal{K}_i)_{0 \leq i \leq p}\), \(\text{minsup}\), \(\text{minconf}\), \(\theta\)

**Output:** correction rules

// Generate basic rules
BasicR := \(\emptyset\)

for all \((\{M^+ (\bar{a}, \bar{b})), M^-(\bar{a}, \bar{b})), \Gamma(\bar{a}), \forall, i\) \(\in\) PCDataset do

\(r_0 := [\Gamma(\bar{a})] : M^-(\bar{a}, \bar{b}) \rightarrow (M^+(\bar{a}, \bar{b})), M^-(\bar{a}, \bar{b}))\)

BasicR := \(\forall \sigma(r_0) \in C \subseteq \bar{a} \cup \bar{b}, \sigma : C \rightarrow \text{Var},\)

\[\text{sup}_{\text{rule}}(\sigma(r_0)) \geq \text{minsup}, \text{conf}(\sigma(r_0)) \geq \text{minconf}\}

// Refine the context part of the rules
\(q := [\{}\), \(q\).enqueueAll(BasicR)

while \(q\) is not empty do

\(r := q\).dequeue()

Output \(r\)

for all operators \(\text{op}\) do

for all \(r' \in \text{op}(r)\) do

if \( \text{sup}_{\text{rule}}(r') \geq \text{minsup}\) and \(\text{conf}(r') \geq \text{conf}(r) + \theta\) then \(q\).enqueue(\(r'\))

Algorithm 2 shows our mining algorithm. It takes as input the PCDataset computed by Algorithm 1, the KB history, a minimum support threshold, a minimum confidence threshold, and a regularization threshold \(\theta\). These thresholds are chosen empirically (see Section 7.3). The algorithm produces correction rules (Definition 8). For this purpose, it first generates a trivial rule \(r_0\) for each entry of the PCDataset. This rule has as context simply the deletion part of the constraint past correction. This trivial rule is then transformed into several more general rules, which we call basic rules, each of which is obtained from \(r_0\) by replacing some of the constants by variables. Formally, the algorithm uses all partial substitutions \(\sigma\) from constants to distinct fresh variables. It retains only those basic rules that meet the minimum support and confidence thresholds.

In the second step, the algorithm incrementally refines each rule by building up its context part \(E(\bar{x}, \bar{y}, \bar{z})\). This works similarly to the mining algorithm of [14]: Each refinement step adds one atom built from the KB concept and role names and the variables and constants that appear in the rule, plus at most one fresh variable. For this purpose, the algorithm uses the operators defined in [14]. If the resulting rule meets the minimum support threshold, and improves the confidence by at least \(\theta\), the rule is retained.

Note that Algorithm 2 outputs only rules that would have been returned by the algorithm of [13, 14] if evaluated with our confidence function. It prunes more rules because of the use of the \(\theta\) and the \(\text{minconf}\) thresholds that are also used to do an early pruning of the rules during the context construction. Algorithm 2 can be easily parallelized by running it independently on each constraint and/or having multiple workers working on the same queue.

**Applying correction rules.** When all rules have been mined, they are sorted by decreasing confidence, breaking ties by help of the support (as it is done in [26] to build classifiers from rules). This set of rules then forms a program that can be used to fix constraint violations as follows. Given a violation \(V\) of a constraint \(\Gamma\) in \(\mathcal{K}\), choose the first rule \(r\) in the program that is relevant for \(\Gamma\) (i.e., that contains \(\Gamma(\bar{x})\) where \(\Gamma(\bar{x})\) is a partially instantiated version of \(\Gamma\)). Then check whether \(r\) can be applied to \(V\). The correction is the result of the rule application.

**Example 7:** Assume we mined the rules \(r_1\) and \(r_2\) of the preceding example with confidence 0.9 and 0.8 respectively, and another rule \(r_3 := [\Gamma_0(x)] : \{\text{hasGender}(x, y)\} \rightarrow (\emptyset, \text{hasGender}(x, y))\) with confidence 0.5. The correction program is \((r_1, r_2, r_3)\). To correct a violation of \(\Gamma_0\), i.e. a wrong value for the hasGender property, the program first checks whether \(r_1\) is applicable. If so, it replaces masculine by male. Otherwise, it falls back to \(r_3\) and removes the wrong value. To correct a violation of \(\Gamma_2\), it ignores \(r_1\) that is not related to \(\Gamma_2\) and either applies \(r_2\) if the context matches or does nothing.

**7 EXPERIMENTS ON WIKIDATA**

This section describes CorHist, which implements the framework introduced for Wikidata, and presents its experimental evaluation.

**7.1 Wikidata**

Wikidata is a generalist collaborative knowledge base. The project started in 2012, and as of July 2018, it has collected more than 500M statements about 50M entities. The data about each entity is stored in a versioned JSON blob, and there are more than 700M revisions. Wikidata encodes facts not in plain RDF triples but in a reified representation, in which each main data property constraint. The remaining constraints are mainly about string format validation with regular expressions (52% of the remaining constraints) and about qualifiers (31% of them).

**7.2 Dataset Construction**

We stored the RDF version [10, 18] of the Wikidata edit history in an RDF quad store. We used named graphs for the global state of Wikidata after each revision, and for the triple additions and deletions. Our dataset stores 390M annotated triples about 49M items extracted from the July 1st, 2018 full database dump.

We extracted the relevant past corrections as explained in Section 6.1. Wikidata revisions do not correspond exactly to atomic modifications in our sense. For example, Wikidata bots are able to change multiple unrelated facts about the same entity at the same time.
Table 3: Wikidata property constraints. \( R \) is the property for which the constraint is given. A constraint has several lines when it uses a property whose set of values may be specified or not. \(|\text{constr.|} is the total number of constraints of the given type in Wikidata. \(|\text{triples|} is the sum for all these constraints of the numbers of triples with the property \( R \) on which they apply. \(|\text{violations|} is the number of violations for this constraint in Wikidata on July 1st, 2018. \(|\text{past cor.|} is the number of past corrections we extracted from Wikidata history. t.o. indicates that we were not able to extract all past corrections because of timeout so that we sample them (we then indicate the number of corrections we extracted).

| Name in Wikidata | DL form | Rule form | \(|\text{constr.| | \(|\text{triples| | \(|\text{violations| | \(|\text{past cor.| |
|-----------------|---------|----------|--------|---------|--------|--------|
| Type \(^4\) | \( \exists R \sqsubseteq A_1 \sqcup \cdots \sqcup A_n \) | \( \exists y(R(x, y) \to A_1(x) \lor \cdots \lor A_n(x)) \) | 2575 | 249M | 3465k | t.o.(-16M) |
| Value type \(^4\) | \( \exists R' \sqsubseteq A_1 \sqcup \cdots \sqcup A_n \) | \( \exists y(R(y, x) \to A_1(x) \lor \cdots \lor A_n(x)) \) | 696 | 67M | 3062k | t.o.(-19M) |
| One-of | \( \exists R' \sqsubseteq \{a_1, \ldots, a_n\} \) | \( \exists y(R(y, x) \to x = a_1 \lor \cdots \lor x = a_n) \) | 104 | 3.6M | 4k | 14k |
| Item requires statement | \( \exists R \sqsubseteq \exists R', \{a_1, \ldots, a_n\} \) | \( \exists y(R(x, y) \to R'(x, a_1) \lor \cdots \lor R'(x, a_n)) \) | 3102 | 255M | 3710k | t.o.(-15M) |
| Value requires statement | \( \exists R' \sqsubseteq \exists R', \{a_1, \ldots, a_n\} \) | \( \exists y(R(y, x) \to \exists z R'(x, z)) \) | 243 | 85M | 1345k | t.o.(-6M) |
| Conflict with | \( \exists R \sqsubseteq \neg \exists R', \{a_1, \ldots, a_n\} \) | \( \exists y(R(x, y) \land (R'(x, a_1) \lor \cdots \lor R'(x, a_n))) \lor false \) | 601 | 449M | 142k | 465k |
| Inverse/Symmetric\(^5\) | \( R \sqsubseteq R'^{-} \) | \( R(x, y) \to R'(y, x) \) | 146 | 6M | 409k | 2989k |
| Single value (func \( R \)) | | \( R(x, y) \land R(z, x) \rightarrow y = z \) | 2772 | 85M | 334k | 389k |
| Distinct values (func \( R^{-} \)) | | \( R(y, x) \land R(z, x) \rightarrow y = z \) | 2728 | 56M | 189k | 7432k |

The Wikidata constraint Type can be qualified to modify its meaning. We ignore these cases, which are marginal: they concern less than 6% of the Type constraints. The same goes analogously for Value type.

\(^5\) Inverse and Symmetric are two distinct kinds of constraints in Wikidata but we treat them together since Symmetric is actually a special case of Inverse.

For each constraint. In practice, it affects only the most frequent 0.9% of Type, 2% of Value type, 0.5% of Item requires statement, and 3% of Value requires statement constraints.

7.3 Mining Rules

The output of our method is a set of correction rules that form a program (Section 6.2). To evaluate such a program, we apply it to each of the constraint violations stored in the PCDataset, using the associated stage of the KB to evaluate the part of the context which is not the deletion part of the correction. Then we check whether the correction we compute is exactly the same as the one associated to the constraint violation in the PCDataset. The precision \( p \) of the program is given by the fraction of the corrections computed by the program that are actually the same as those that have been applied. The recall \( r \) of the program is the fraction of the constraint violations stored in PCDataset for which the program gives some correction. The F1 score is \( F_1 = \frac{2rp}{p+r} \).

CorHist mines rules as explained in Section 6.2. In order to decrease the computation time, we only allow one atom \( p(x, o) \) in \( E(\overline{x}, \overline{y}, \overline{z}) \setminus Body(\overline{x}, \overline{y}) \), where \( Body(\overline{x}, \overline{y}) \) corresponds to the part of the context that matches part of the constraint body, such that \( s \) is a variable of \( \overline{x} \cup \overline{y} \) and \( o \) is a fresh variable or a constant.

Rules were mined per constraint. For each constraint, we split the set of extracted past corrections into a 70% training set, a 10% cross-validation set, and a 20% test set. The training set is used to mine the rules, the cross-validation set is used to determine the confidence threshold that maximizes the F1 score of the obtained program, and the test set is used to evaluate the final program.

Table 4 gives examples of rules mined by CorHist. Several of these rules show the crucial importance of the instantiation of the constraint and/or of the context to be able to choose the correction. For instance, the rule for the Single value constraint uses the fact that an entity involved in a property “member of sport team” is
probably a human being, and thus that it has several values for the functional property "sex or gender" and one of them is a value reserved for non-human organisms in Wikidata, this value is probably wrong. In the same vein, the rule for the Item requires statement constraint recognizes that an entity has a heritage designation that is specific to Sweden (“monument in Formminnesregistret”), to conclude that its country is Sweden. The rules also propose fixes to misused predicates: in Wikidata, the property “manner of death” is intended for the general circumstances of a person’s death (such as “accident”), while the property “cause of death” is intended to give more precise causes (such as “traffic accident”).

### 7.4 Evaluation against the Test Set

Table 5 presents the results of the evaluation of the mined programs against the test set. We computed both the micro and macro average of the precision, recall and F1 score per kind of constraint. The micro average aggregates over the whole set of relevant past corrections for the given kind of constraint, whereas the macro average computes the scores for each constraint of this given kind, and then computes the average. Both numbers are important: The micro average gives more weight to correction rules that fix many violations. It thus measures the overall impact of the correction rules on the dataset. However, if few rules had a large impact, then it would be easier to formulate these rules by hand. Our method, in contrast, can also find rules that by themselves solve less violations, but together contribute a large mass of corrections. To illustrate this, we also report the macro average: It measures the average performance across different constraints.

We compare our approach with two baselines: The first one, called “delete”, is the most basic one and uses the fact that all Wikidata constraint bodies contain an atom of the form $R(x, y)$ and the TBox contains only concept inclusions, so that all constraint violations contain an assertion that matches $R(x, y)$. The “delete” baseline simply deletes this assertion. For the completeness constraints we define an additional baseline, “add”, which tries to add a new triple to solve the constraint violation. For Inverse and Symmetric constraints this baseline adds the missing reverse edge and performs very well. For Item requires statement, Value requires statement, Type and Value type, it adds the missing triple only if it is possible to know the expected value from the constraint rule.

---

Table 4: Example of mined rules.

<table>
<thead>
<tr>
<th>Constr. type</th>
<th>Constraint $\Gamma$</th>
<th>Correction rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>$\exists$isListOf $\subseteq$ List</td>
<td>$[\Gamma(s)] : \text{isListOf}(s, o) \land \text{WikiDisambiguationPage}(s) \rightarrow (\emptyset, \text{isListOf}(s, o))$</td>
</tr>
<tr>
<td>Value type</td>
<td>$\exists$foundInTax $\subseteq$ Taxon</td>
<td>$[\Gamma(\text{human})] : \text{foundInTax}(s, \text{human}) \land \text{hasPart}(s, v) \rightarrow (\text{foundInTax}(s, \text{homoSapiens}), \text{foundInTax}(s, \text{human}))$</td>
</tr>
<tr>
<td>One-of</td>
<td>$\exists$mannerOfDeath $\in {\ldots}$</td>
<td>$[\Gamma(\text{trafficAcc})] : \text{mannerOfDeath}(s, \text{trafficAcc}) \rightarrow (\text{causeOfDeath}(s, \text{trafficAcc}), \text{mannerOfDeath}(s, \text{trafficAcc}))$</td>
</tr>
<tr>
<td>Item req. stm.</td>
<td>$\exists$heritageStatus $\subseteq$ $\exists$country</td>
<td>$[\Gamma(s)] : \text{heritageStatus}(s, \text{monumentInFormminnesregistret}) \rightarrow (\text{country}(s, \text{Sweden}), \emptyset)$</td>
</tr>
<tr>
<td>Val. req. stm.</td>
<td>$\exists$residence $\subseteq$ $\exists$Country</td>
<td>$[\Gamma(s)] : \text{dipomaticRelation}(s, v) \rightarrow (\text{country}(s, \emptyset), \emptyset)$</td>
</tr>
<tr>
<td>Conflict</td>
<td>$\exists$filmplID $\subseteq$ $\neg\exists$filmplFilmID</td>
<td>$[\Gamma(s)] : \text{filmplID}(s, o) \rightarrow (\emptyset, \text{filmplID}(s, o))$</td>
</tr>
<tr>
<td>Inv./Sym.</td>
<td>$\exists$geneticAssoc $\subseteq$ $\exists$geneticAssoc</td>
<td>$[\Gamma(s)] : \text{sexOrGender}(s, \text{maleOrg}) \land \text{sportsTeam}(s, v) \rightarrow (\emptyset, \text{sexOrGender}(s, \text{maleOrg}))$</td>
</tr>
</tbody>
</table>

Table 5: Evaluation of the correction rules mined by CorHist with a minimal support of 10, a minimal confidence between 0.3 and 1 and a regularization threshold of 0.05, and comparison with the baselines. Best precision and F1 scores in bold.

<table>
<thead>
<tr>
<th>Constraint type</th>
<th>Micro average</th>
<th>Macro average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prec.</td>
<td>Rec.</td>
</tr>
<tr>
<td>Type6</td>
<td>add</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>delete</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>CorHist</td>
<td>0.84</td>
</tr>
<tr>
<td>Value type6</td>
<td>add</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>delete</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>CorHist</td>
<td>0.81</td>
</tr>
<tr>
<td>One-of</td>
<td>delete</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>CorHist</td>
<td>0.77</td>
</tr>
<tr>
<td>Item requires statement6</td>
<td>delete</td>
<td>0.017</td>
</tr>
<tr>
<td></td>
<td>CorHist</td>
<td>0.94</td>
</tr>
<tr>
<td>Value requires statement6</td>
<td>add</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>delete</td>
<td>0.041</td>
</tr>
<tr>
<td></td>
<td>CorHist</td>
<td>0.91</td>
</tr>
<tr>
<td>Conflict with</td>
<td>delete</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td>CorHist</td>
<td>0.92</td>
</tr>
<tr>
<td>Inverse/Sym.</td>
<td>add</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>delete</td>
<td>0.072</td>
</tr>
<tr>
<td></td>
<td>CorHist</td>
<td>0.92</td>
</tr>
<tr>
<td>Single value</td>
<td>delete</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>CorHist</td>
<td>0.95</td>
</tr>
<tr>
<td>Distinct values</td>
<td>delete</td>
<td>0.036</td>
</tr>
<tr>
<td></td>
<td>CorHist</td>
<td>0.99</td>
</tr>
</tbody>
</table>

For example, for Type constraints of the form $3yR(x, y) \rightarrow A(x)$ it applies the correction $(A(x), \emptyset)$. Value type constraints are handled in the same way. However, this baseline is not able to figure out what is the relevant addition correction for a constraint of the form $3yR(x, y) \rightarrow A_1(x) \lor A_2(x)$ because there is no way to know a priori if $A_1$ or $A_2$ should be added. For Item requires statement constraints of the form $3yR(x, y) \rightarrow R'(x, a)$, the “add” baseline applies $(R'(x, a), \emptyset)$ (similarly for Value requires statement constraints). However, it cannot find a correction if there are multiple $a_i$.  

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[1] Computed from a sample of the set of relevant past corrections. One Type constraint, six Value type constraints and one Val. req. stm constraint were omitted due to time-out.

[2] The actual value is greater than 0.995 and rounded to 1 for consistency.
An entity should not have a statement for country of citizenship if it also has a statement for sex or gender with value male non-human organism.

Possible correction
Edit statement (Q57082102, sex or gender, male non-human organism). Setting value to: male

For the constraints which got a significant number of evaluations, our approach seems to perform well for Inverse and Symmetric, Conflict with and Value requires statement constraints, with approval rates above 80%. The other approval rates are lower. This is partly due to biases in the data. For example, when a gender is missing, our approach proposes the value “male” by default, because of the over-representation of men in Wikidata. Another issue is the quality of the constraints, which in Wikidata are sometimes questionable or difficult to understand (e.g., an incomplete set of possible types or values for completeness or One-of constraints).

However, even lower approval scores do not mean that our approach would be useless: Psychological research [12] shows that people find it much easier to choose from given options than to come up with an answer by themselves. The actual time needed to come up with an answer may vary, but if it takes just 3 times longer to come up with an answer than to accept or reject our proposed correction, then achieving a precision of 40% is already useful: If we have a precision of 40%, and if a free-form answer takes time t, then the expected answer time with our tool is $40\% \times \frac{1}{3} \times t + 60\% \times \frac{1}{4} \times t < t$.

8 CONCLUSION AND FUTURE WORK
We have introduced the problem of learning how to fix constraint violations from a KB history. We have also presented a method based on rule mining to this end. Our experimental evaluation on Wikidata shows significant improvement over baselines. Our tool is live on Wikidata and has already allowed users to correct more than 23k constraint violations. While our evaluation focused on Wikidata for which the whole edit history was available, we believe that our method can be applied in other settings, for example using edits done during the partial cleaning of an automatically extracted KB.

For future work, it would be interesting to evaluate the impact of parameters such as the size of the context part of the correction rule in terms of rule quality. We also plan to extend the learning dataset with external knowledge (such as other KBs), or with information extracted from other sources (for instance from Wikipedia). We believe that this will allow finding even more precise correction rules, thus making KBs ever more precise and more useful.

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