Updating RDFS ABoxes and TBoxes in SPARQL

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Abstract. Updates in RDF stores have recently been standardised in the SPARQL 1.1 Update specification. However, computing entailed answers by ontologies is usually treated orthogonally to updates in triple stores. Even the W3C SPARQL 1.1 Update and SPARQL 1.1 Entailment Regimes specifications explicitly exclude a standard behaviour for entailment regimes other than simple entailment in the context of updates. In this paper, we take a first step to close this gap. We define a fragment of SPARQL basic graph patterns corresponding to (the RDFS fragment of) *DL-Lite* and the corresponding SPARQL update language, dealing with updates both of ABox and of TBox statements. We discuss possible semantics along with potential strategies for implementing them. In particular, we treat both, (i) materialised RDF stores, which store all entailed triples explicitly, and (ii) reduced RDF Stores, that is, redundancy-free RDF stores that do not store any RDF triples (corresponding to *DL-Lite* ABox statements) entailed by others already. We have implemented all semantics prototypically on top of an off-the-shelf triple store and present some indications on practical feasibility.

1 Introduction

The availability of SPARQL as a standard for accessing structured Data on the Web may well be called one of the key factors to the success and increasing adoption of RDF and the Semantic Web. Still, in its first iteration the SPARQL [24] specification has neither defined how to treat ontological entailments with respect to RDF Schema (RDFS) and OWL ontologies, nor provided means how to update dynamic RDF data. Both these gaps have been addressed within the recent SPARQL 1.1 specification, which provides both means to define query answers under ontological entailments (SPARQL 1.1 Entailment Regimes [9]), and an update language to update RDF data stored in a triple store (SPARQL 1.1 Update [8]). Nonetheless, these specifications leave it open how SPARQL endpoints should treat entailment regimes other than simple entailment in the context of updates; the main issue here is how updates shall deal with implied statements:

- What does it mean if an implied triple is explicitly (re-)inserted (or deleted)?
- Which (if any) additional triples should be inserted, (or, resp., deleted) upon updates?

For the sake of this paper, we address such questions with the focus on a deliberately minimal ontology language, namely the minimal RDFS fragment of [19].[4] As it turns out,

[4] We ignore issues like axiomatic triples [13], blank nodes [17], or, in the context of OWL, inconsistencies arising through updates [5]. Neither do we consider named graphs in SPARQL, which is why we talk about "triple stores" as opposed to "graph stores" [8].

Table 1. *DL-Lite*$_{\text{RDFS}}$ assertions vs. RDF(S), where A, A' denote concept (or, class) names, P, P' denote role (or, property) names, Γ is a set of constants, and $x, y \in \Gamma$. For RDF(S) vocabulary, we make use of similar abbreviations (sc, sp, dom, rng, a) introduced in [19].

	TBox	RDFS
1	$A' \sqsubseteq A$	A' sc A.
2	$P' \sqsubseteq P$	P' sp P.

	TBox	RDFS
3	$\exists P \sqsubseteq A$	P dom A.
4	$\exists P^- \sqsubseteq A$	P rng A.

	ABox	RDFS
5	$A(x)$	x a A.
6	$P(x, y)$	x P y.

even in this confined setting, updates as defined in the SPARQL 1.1 Update specification impose non-trivial challenges; in particular, specific issues arise through the interplay of INSERT, DELETE, and WHERE clauses within a single SPARQL update operation, which —to the best of our knowledge— have not yet been considered in this combination in previous literature on updates under entailment (such as for instance [5, 11]).

Example 1. As a running example, we assume a triple store G with RDF (ABox) data and an RDFS ontology (TBox) O_{fam} about family relationships (in Turtle syntax [2]), where `:hasP`, `:hasM`, and `:hasF`, resp., denote the parent, mother, and father relations.

```
ABox:  :joe :hasP :jack.      :joe :hasM :jane.
TBox:  :Father sc :Parent.    :Mother sc :Parent.
  :hasF sp :hasP.      :hasM sp :hasP.
  :hasF rng :Father; dom :Child. :hasM rng :Mother; dom :Child.
  :hasP rng :Parent; dom :Child.
```

The following query should return `:jack` and `:jane` as (RDFS entailed) answers:

```
SELECT ?Y WHERE { :joe :hasP ?Y. }
```

SPARQL engines supporting simple entailment would only return `:jack`, though. ■

The intended behaviour for the query in Ex. 1 is typically achieved by either *(i)* query rewriting techniques computing entailed answers at query run-time, or *(ii)* by materialising all implied triples in the store, normally at loading time. That is, on the one hand, borrowing from query rewriting techniques from *DL-Lite* (such as, e.g., *PerfectRef* [4][5]) one can reformulate such a query to return also implied answers. While the rewritten query is worst case exponential wrt. the length of the original query (and polynomial in the size of the TBox), for moderate size TBoxes and queries rewriting is quite feasible.

Example 2 (cont'd). The rewriting of the query in Ex. 1 according to *PerfectRef* [4] with respect to O_{fam} as a DL TBox in SPARQL yields

```
SELECT ?Y WHERE { {:joe :hasP ?Y}
                  UNION {:joe :hasF ?Y}  UNION {:joe :hasM ?Y}}
```

Indeed, this query returns both `:jane` and `:jack`. ■

On the other hand, an alternative[6] is to materialise all inferences in the triple store, such that the original query can be used 'as is', for instance using the minimalistic inference rules for RDFS from [19][7] shown in Fig. 1.

[5] Alg. 1 in the Appendix shows a version of *PerfectRef* reduced to the essentials of RDFS.

[6] This alternative is viable for RDFS, but not necessarily for more expressive DLs.

[7] These rules correspond to rules 2), 3), 4) of [19]; they suffice since we ignore blank nodes.

Example 3 (cont'd). The materialised version of G would contain the following triples—for conciseness we only show assertional implied triples here, that is triples from the four leftmost rules in Fig. 1.

```
:joe a :Child; :hasP :jack; :hasM :jane; :hasP :jane.
:jack a :Parent. :jane a :Mother, :Parent.
```

On a materialised triple store, the query from Ex. 1 would return the expected results. ■

However, in the context of SPARQL 1.1 Update, things become less clear.

Example 4 (cont'd). The following operation tries to delete an implied triple and at the same time to (re-)insert another implied triple.

```
DELETE {?X a :Child} INSERT {?Y a :Mother} WHERE {?X :hasM ?Y}
```
■

Existing triple stores offer different solutions to these problems, ranging from ignoring entailments in updates altogether, to keeping explicit and implicit (materialised) triples separate and re-materialising upon updates. In the former case (ignoring entailments) updates only refer to explicitly asserted triples, which may result in non-intuitive behaviours, whereas the latter case (re-materialisation) may be very costly, while still not eliminating all non-intuitive cases, as we will see. The problem is aggravated by no systematic approach to the question of which implied triples to store explicitly in a triple store and which not. In this paper we try to argue for a more systematic approach for dealing with updates in the context of RDFS entailments. More specifically, we will distinguish between two kinds of triple stores, that is *(i) materialised RDF stores*, which store all entailed ABox triples explicitly, and *(ii) reduced RDF Stores*, that is, redundancy-free RDF stores that do not store any assertional (ABox) triples already entailed by others. We propose alternative update semantics that preserve the respective types *(i)* and *(ii)* of triple stores, and discuss possible implementation strategies, partially inspired by query rewriting techniques from ontology-based data access (OBDA) [15] and *DL-Lite* [4]. As already shown in [11], erasure of ABox statements is deterministic in the context of RDFS, but insertion and particularly the interplay of DELETE/INSERT in SPARQL 1.1 Update has not been considered therein. Finally, we relax the initial assumption that terminological statements (using the RDFS vocabulary) are static, and discuss the issues that arise when also TBox statement are subject to updates.

The remainder of the paper continues with preliminaries (RDFS, SPARQL, *DL-Lite*, SPARQL update operations) in Sec. 2. We introduce alternative semantics for ABox updates in materialised and reduced triple stores in Sec. 3, and discuss them in Sec. 4 and Sec. 5, respectively. In Sec. 6, we present our results on TBox updates. After presenting in Sec. 7 an implementation on top of an off-the-shelf triple store along with experiments, followed in Sec. 8 by a discussion of future and related work, we conclude in Sec. 9.

$$\frac{?C\ \mathsf{sc}\ ?D. \quad ?S\ \mathsf{a}\ ?C.}{?S\ \mathsf{a}\ ?D.} \qquad \frac{?P\ \mathsf{dom}\ ?C. \quad ?S\ ?P\ ?O.}{?S\ \mathsf{a}\ ?C.} \qquad \frac{?C\ \mathsf{sc}\ ?D. \quad ?D\ \mathsf{sc}\ ?E.}{?C\ \mathsf{sc}\ ?E.}$$

$$\frac{?P\ \mathsf{sp}\ ?Q. \quad ?S\ ?P\ ?O.}{?S\ ?Q\ ?O.} \qquad \frac{?P\ \mathsf{rng}\ ?C. \quad ?S\ ?P\ ?O.}{?O\ \mathsf{a}\ ?C.} \qquad \frac{?P\ \mathsf{sp}\ ?Q. \quad ?Q\ \mathsf{sp}\ ?R.}{?P\ \mathsf{sp}\ ?R.}$$

Fig. 1. Minimal RDFS inference rules

2 Preliminaries

We introduce some basic notions about RDF graphs, RDFS ontologies, and SPARQL queries. Since we will draw from ideas coming from OBDA and *DL-Lite*, we introduce these notions in a way that is compatible with DLs.

Definition 1 (RDFS ontology, ABox, TBox, triple store). *We call a set $\mathcal{T}$ of inclusion assertions of the forms 1–4 in Table 1 an* RDFS ontology*, or* (RDFS) TBox*, a set $\mathcal{A}$ of assertions of the forms 5–6 in Table 1 an* (RDF) ABox*, and the union $G = \mathcal{T} \cup \mathcal{A}$ an* (RDFS) triple store*.*

In the context of RDF(S), the set Γ of constants coincides with the set I of IRIs. We assume the IRIs used for concepts, roles, and individuals to be disjoint from IRIs of the RDFS and OWL vocabularies.[8] In the following, we view RDF and DL notation interchangeably, i.e., we treat any RDF graph consisting of triples without non-standard RDFS vocabulary as a set of TBox and ABox assertions. To define the semantics of RDFS, we rely on the standard notions of (first-order logic) *interpretation*, satisfaction of assertions, and *model* (cf. e.g., [1, Def. 14]).

As for queries, we again treat the cases of SPARQL and DLs interchangeably. Let $\mathcal{V}$ be a countably infinite set of variables (written as '?'-prefixed alphanumeric strings).

Definition 2 (BGP, CQ, UCQ). *A* conjunctive query *(CQ) q, or* basic graph pattern (BGP)*, is a set of atoms of the forms 5–6 from Table 1, where now $x, y \in \Gamma \cup \mathcal{V}$. A* union of conjunctive queries *(UCQ) Q, or* UNION *pattern, is a set of CQs. We denote with $\mathcal{V}(q)$ (or $\mathcal{V}(Q)$) the set of variables from $\mathcal{V}$ occurring in q (resp., Q).*

Notice that in this definition we are considering only CQs in which all variables are *distinguished* (i.e., are answer variables), and that such queries correspond to SPARQL basic graph patterns (BGPs). From the SPARQL perspective, we allow only for restricted forms of general SPARQL BGPs that correspond to standard CQs as formulated over a DL ontology; that is, we rule out on the one hand more complex patterns in SPARQL 1.1 [12] (such as OPTIONAL, NOT EXISTS, FILTER), and queries with variables in predicate positions, and on the other hand "terminological" queries, e.g., $\{?x \ \mathsf{sc} \ ?y.\}$. We will relax this latter restriction later (see Sec. 6). Also, we do not consider here blank nodes separately[9]. By these restrictions, we can treat query answering and BGP matching in SPARQL analogously and define it in terms of interpretations and models (as usual in DLs). Specifically, an *answer* (under RDFS Entailment) to a CQ q over a triple store G is a substitution θ of the variables in $\mathcal{V}(q)$ with constants in Γ such that every model of G satisfies all facts in $q\theta$. We denote the set of all such answers with $ans_{\mathsf{rdfs}}(q, G)$ (or simply $ans(q, G)$). The set of answers to a UCQ Q is $\bigcup_{q \in Q} ans(q, G)$.

From now on, let $rewrite(q, \mathcal{T})$ be the UCQ resulting from applying $PerfectRef$ (or, equivalently, the down-stripped version Alg. 1) to a CQ q and a triple store $G = \mathcal{T} \cup \mathcal{A}$,

[8] That is, we assume no "non-standard use" [23] of these vocabularies. While we could assume concept names, role names, and individual constants mutually disjoint, we rather distinguish implicitly between them "per use" (in the sense of "punning" [18]) based on their position in atoms or RDF triples.

[9] Blank nodes in a triple store may be considered as constants and we do not allow blank nodes in queries, which does not affect the expressivity of SPARQL.

and let $mat(G)$ be the triple store obtained from exhaustive application on G of the inference rules in Fig. 1.

The next result follows immediately from, e.g., [4, 11, 19] and shows that query answering under RDF can be done by either query rewriting or materialisation.

Proposition 1. *Let $G = \mathcal{T} \cup \mathcal{A}$ be a triple store, q a CQ, and $\mathcal{A}'$ the set of ABox assertions in $mat(G)$. Then, $ans(q, G) = ans(rewrite(q, \mathcal{T}), \mathcal{A}) = ans(q, \mathcal{A}')$.*

Various triple stores (e.g., BigOWLIM [3]) perform ABox materialisation directly upon loading data. However, such triple stores do not necessarily materialise the TBox: in order to correctly answer UCQs as defined above, a triple store actually does not need to consider the two rightmost rules in Fig. 1. Accordingly, we will call a triple store or (ABox) *materialised* if in each state it always guarantees $G \setminus \mathcal{T} = mat(G) \setminus mat(\mathcal{T})$. On the other extreme, we find triple stores that do not store *any* redundant ABox triples. By $red(G)$ we denote the hypothetical operator that produces the reduced "core" of G, and we call a triple store *(ABox) reduced* if $G = red(G)$. We note that this core is uniquely determined in our setting whenever $\mathcal{T}$ is acyclic (which is usually a safe assumption)[10]; it could be naïvely computed by exhaustively "marking" each triple that can be inferred from applying any of the four leftmost rules in Fig. 1, and subsequently removing all marked elements of $\mathcal{A}$. Lastly, we observe that, trivially, a triple store containing no ABox statements is both reduced and materialised.

Finally, we introduce the notion of a SPARQL update operation.

Definition 3 (SPARQL update operation). *Let P_d and P_i be BGPs, and P_w a BGP or UNION pattern. Then an* update operation $u(P_d, P_i, P_w)$ *has the form*

$$\texttt{DELETE}\ \ P_d\ \ \texttt{INSERT}\ \ P_i\ \ \texttt{WHERE}\ \ P_w.$$

Intuitively, the semantics of executing $u(P_d, P_i, P_w)$ on G, denoted as $G_{u(P_d,P_i,P_w)}$ is defined by interpreting both P_d and P_i as "templates" to be instantiated with the solutions of $ans(P_w, G)$, resulting in sets of ABox statements $\mathcal{A}_d$ to be deleted from G, and $\mathcal{A}_i$ to be inserted into G. A naïve update semantics follows straightforwardly.

Definition 4 (Naïve update semantics). *Let $G = \mathcal{T} \cup \mathcal{A}$ be a triple store, and $u(P_d, P_i, P_w)$ an update operation. Then,* naive update of G with $u(P_d, P_i, P_w)$*, denoted $G_{u(P_d,P_i,P_w)}$, is defined as $(G \setminus \mathcal{A}_d) \cup \mathcal{A}_i$, where $\mathcal{A}_d = \bigcup_{\theta \in ans(P_w,G)} gr(P_d\theta)$, $\mathcal{A}_i = \bigcup_{\theta \in ans(P_w,G)} gr(P_i\theta)$, and $gr(P)$ denotes the set of ground triples in pattern P.*

As easily seen, this naïve semantics neither preserves reduced nor materialised triple stores. Consider, e.g., the update from Ex. 4, respectively on the reduced triple store from Ex. 1 and on the materialised triple store from Ex. 3.

[10] We note that even in the case when the TBox is cyclic we could define a deterministic way to remove redundancies, e.g., by preserving within a cycle only the lexicographically smallest ABox statements. That is, given TBox $A \sqsubseteq B \sqsubseteq C \sqsubseteq A$ and ABox $A(x), C(x)$; we would delete $C(x)$ and retain $A(x)$ only, to preserve reducedness.

3 Defining Alternative Update Semantics

We investigate now alternative semantics for updates that preserve either materialised or reduced ABoxes, and discuss how these semantics can—similar to query answering—be implemented in off-the-shelf SPARQL 1.1 triple stores.

Definition 5 (Mat-preserving and red-preserving semantics). *Let G and $u(P_d, P_i, P_w)$ be as in Def. 4. An update semantics Sem is called* mat-preserving*, if $G^{Sem}_{u(P_d,P_i,P_w)} = mat(G^{Sem}_{u(P_d,P_i,P_w)})$, and it is called* red-preserving*, if $G^{Sem}_{u(P_d,P_i,P_w)} = red(G^{Sem}_{u(P_d,P_i,P_w)})$.*

Specifically, we consider the following variants of materialised ABox preserving (or simply, *mat-preserving*) semantics and reduced ABox preserving (or simply, *red-preserving*) semantics, given an update $u(P_d, P_i, P_w)$:

Sem$_0^{mat}$: As a baseline for a mat-preserving semantics, we apply the naïve semantics, followed by (re-)materialisation of the whole triple store.

Sem$_1^{mat}$: An alternative approach for a mat-preserving semantics is to follow the so-called "delete and rederive" algorithm [10] for deletions, that is: *(i)* delete the instantiations of P_d *plus "dangling" effects*, i.e., effects of deleted triples that after deletion are not implied any longer *by any non-deleted triples*; *(ii)* insert the instantiations of P_i *plus all their effects*.

Sem$_2^{mat}$: Another mat-preserving semantics could take a different viewpoint with respect to deletions, following the intention to: *(i)* delete the instantiations of P_d *plus all their causes*; *(ii)* insert the instantiations of P_i *plus all their effects*.

Sem$_3^{mat}$: Finally, a mat-preserving semantics could combine **Sem**$_1^{mat}$ and **Sem**$_2^{mat}$, by deleting both causes of instantiations of P_d and (recursively) "dangling" effects.[11]

Sem$_0^{red}$: Again, the baseline for a red-preserving semantics would be to apply the naïve semantics, followed by (re-)reducing the triple store.

Sem$_1^{red}$: This red-preserving semantics extends **Sem**$_0^{red}$ by additionally deleting the causes of instantiations of P_d.

The definitions of semantics **Sem**$_0^{mat}$ and **Sem**$_0^{red}$ are straightforward.

Definition 6 (Baseline mat-preserving and red-preserving update semantics). *Let G and $u(P_d, P_i, P_w)$ be as in Def. 4. Then, we define* **Sem**$_0^{mat}$ *and* **Sem**$_0^{red}$ *as follows:*

$$G^{\mathbf{Sem}_0^{mat}}_{u(P_d,P_i,P_w)} = mat(G_{u(P_d,P_i,P_w)}) \qquad G^{\mathbf{Sem}_0^{red}}_{u(P_d,P_i,P_w)} = red(G_{u(P_d,P_i,P_w)})$$

Let us proceed with a quick "reality-check" on these two baseline semantics by means of our running example.

Example 5. Consider the update from Ex. 4. It is easy to see that neither under **Sem**$_0^{mat}$ executed on the materialised triple store of Ex. 3, nor under **Sem**$_0^{red}$ executed on the reduced triple store of Ex. 1, it would have *any* effect. ■

This behaviour is quite arguable. Hence, we proceed with discussing the implications of the proposed alternative update semantics, and how they could be implemented.

[11] Note the difference to the basic "delete and rederive" approach. **Sem**$_1^{mat}$ in combination with the intention of **Sem**$_2^{mat}$ would also mean to recursively delete effects of causes, and so forth.

4 Alternative Mat-Preserving Semantics

We consider now in more detail the mat-preserving semantics. As for $\mathbf{Sem}_1^{mat}$, we rely on a well-known technique in the area of updates for deductive databases called "delete and rederive" (DRed) [6, 10, 16, 26, 27]. Informally translated to our setting, when given a logic program Π and its materialisation T_Π^ω, plus a set of facts A_d to be deleted and a set of facts A_i to be inserted, DRed *(i)* first deletes A_d and all its effects (computed via semi-naive evaluation [25]) from T_Π^ω, resulting in $(T_\Pi^\omega)'$, *(ii)* then, starting from $(T_\Pi^\omega)'$, re-materialises $(\Pi \setminus A_d) \cup A_i$ (again using semi-naive evaluation).

The basic intuition behind DRed of deleting effects of deleted triples and then re-materialising can be expressed in our notation as follows; as we will consider a variant of this semantics later on, we refer to this semantics as $\mathbf{Sem}_{1a}^{mat}$.

Definition 7. *Let $G = \mathcal{T} \cup \mathcal{A}$, $u(P_d, P_i, P_w)$, $\mathcal{A}_d$, and $\mathcal{A}_i$ be defined as in Def. 4. Then* $G^{\mathbf{Sem}_{1a}^{mat}}_{u(P_d,P_i,P_w)} = mat(\mathcal{T} \cup (\mathcal{A} \setminus mat(\mathcal{T} \cup \mathcal{A}_d)) \cup \mathcal{A}_i)$.

As opposed to the classic DRed algorithm, where Datalog distinguishes between view predicates (IDB) and extensional knowledge in the Database (EDB), in our setting we do not make this distinction, i.e., we do not distinguish between implicitly and explicitly inserted triples. This means that $\mathbf{Sem}_{1a}^{mat}$ would delete also those effects that had been inserted explicitly before.

We introduce now a different variant of this semantics, denoted $\mathbf{Sem}_{1b}^{mat}$, that makes a distinction between explicitly and implicitly inserted triples.

Definition 8. *Let $u(P_d, P_i, P_w)$ be an update operation, and $G = \mathcal{T} \cup \mathcal{A}_{expl} \cup \mathcal{A}_{impl}$ a triple store, where $\mathcal{A}_{expl}$ and $\mathcal{A}_{impl}$ respectively denote the explicit and implicit ABox triples. Then $G^{\mathbf{Sem}_{1b}^{mat}}_{u(P_d,P_i,P_w)} = \mathcal{T} \cup \mathcal{A}'_{expl} \cup \mathcal{A}'_{impl}$, where $\mathcal{A}_d$ and $\mathcal{A}_i$ are defined as in Def. 4, $\mathcal{A}'_{expl} = (\mathcal{A}_{expl} \setminus \mathcal{A}_d) \cup \mathcal{A}_i$, and $\mathcal{A}'_{impl} = mat(\mathcal{A}'_{expl} \cup \mathcal{T}) \setminus \mathcal{T}$.*

Note that in $\mathbf{Sem}_{1b}^{mat}$, as opposed to $\mathbf{Sem}_{1a}^{mat}$, we do not explicitly delete effects of $\mathcal{A}_d$ from the materialisation, since the definition just relies on re-materialisation from scratch from the explicit ABox $\mathcal{A}'_{expl}$. Nonetheless, the original DRed algorithm can still be used for computing $\mathbf{Sem}_{1b}^{mat}$ as shown by the following proposition.

Proposition 2. *Let us interpret the inference rules in Fig. 1 and triples in G respectively as rules and facts of a logic program Π; accordingly, we interpret $\mathcal{A}_d$ and $\mathcal{A}_i$ from Def. 8 as facts to be deleted from and inserted into Π, respectively. Then, the materialisation computed by DRed, as defined in [16], computes exactly $\mathcal{A}'_{impl}$.*

None of $\mathbf{Sem}_0^{mat}$, $\mathbf{Sem}_{1a}^{mat}$, and $\mathbf{Sem}_{1b}^{mat}$ are equivalent, as shown in Ex. 6 below.

Example 6. Given the triple store $G = \{$`:C sc :D . :D sc :E`$\}$, on which we perform the operation `INSERT{:x a :C, :D, :E.}`, *explicitly* adding three triples, and subsequently perform `DELETE{:x a :C, :E.}`, we obtain, according to the three semantics discussed so far, the following ABoxes:
$\mathbf{Sem}_0^{mat}$: `{:x a :D. :x a :E.}` $\mathbf{Sem}_{1a}^{mat}$: `{}`
$\mathbf{Sem}_{1b}^{mat}$: `{:x a :D. :x a :E.}`

While after this update $\mathbf{Sem}_0^{mat}$ and $\mathbf{Sem}_{1b}^{mat}$ deliver the same result, the difference between these two is shown by the subsequent update `DELETE{ :x a :D.}`
$\mathbf{Sem}_0^{mat}$: `{ :x a :E.}` $\mathbf{Sem}_{1a}^{mat}$: `{}` $\mathbf{Sem}_{1b}^{mat}$: `{}` ■

As for the subtle difference between $\mathbf{Sem}_{1a}^{mat}$ and $\mathbf{Sem}_{1b}^{mat}$, we point out that none of [16, 26], who both refer to using DRed in the course of RDF updates, make it clear whether explicit and implicit ABox triples are to be treated differently.

Further, continuing with Ex. 5, the update from Ex. 4 still would not have *any* effect, neither using $\mathbf{Sem}_{1a}^{mat}$, nor $\mathbf{Sem}_{1b}^{mat}$. That is, it is not possible in any of these update semantics to remove implicit information (without explicitly removing all its causes).

$\mathbf{Sem}_2^{mat}$ aims at addressing this problem concerning the deletion of implicit information. As it turns out, while the intention of $\mathbf{Sem}_2^{mat}$ to delete causes of deletions cannot be captured just with the mat operator, it can be achieved fairly straightforwardly, building upon ideas similar to those used in query rewriting.

As we have seen, in the setting of RDFS we can use Alg. 1 $rewrite$ to expand a CQ to a UCQ that incorporates all its "causes". A slight variation can be used to compute the set of all causes, that is, in the most naïve fashion by just "flattening" the set of sets returned by Alg. 1 to a simple set; we denote this flattening operation on a set S of sets as $\mathit{flatten}(S)$. Likewise, we can easily define a modified version of $mat(G)$, applied to a BGP P using a TBox $\mathcal{T}$[12]. Let us call the resulting algorithm $mat_{\mathit{eff}}(P, \mathcal{T})$[13]. Using these considerations, we can thus define both rewritings that consider all causes, and rewritings that consider all effects of a given (insert or delete) pattern P:

Definition 9 (Cause/Effect rewriting). *Given a BGP insert or delete template P for an update operation over the triple store $G = \mathcal{T} \cup \mathcal{A}$, we define the* all-causes-rewriting *of P as $P^{caus} = \mathit{flatten}(rewrite(P, \mathcal{T}))$; likewise, we define the* all-effects-rewriting *of P as $P^{\mathit{eff}} = mat_{\mathit{eff}}(P, \mathcal{T})$.*

This leads (almost) straightforwardly to a rewriting-based definition of $\mathbf{Sem}_2^{mat}$.

Definition 10. *Let $u(P_d, P_i, P_w)$ be an update operation. Then*

$$G^{\mathbf{Sem}_2^{mat}}_{u(P_d,P_i,P_w)} = G_{u(P_d^{caus},P_i^{\mathit{eff}},\{P_w\}\{P_d^{fvars}\})},$$

where $P_d^{fvars} = \{?v$ a rdfs:Resource. $\mid$ *for each* $?v \in Var(P_d^{caus}) \setminus Var(P_d)\}$.

The only tricky part in this definition is the rewriting of the WHERE clause, where P_w is joined[14] with a new pattern P_d^{fvars} that binds "free" variables (i.e., the "fresh" variables denoted by '_' in Table 2, introduced by Alg. 1, cf. Appendix) in the rewritten DELETE clause, P_d^{caus}. Here, `?v a rdfs:Resource.` is a shortcut for a pattern which binds `?v` to any term occurring in G, cf. Sec. 7 below for details.

[12] This could be viewed as simply applying the first four inference rules in Fig. 1 exhaustively to $P \cup \mathcal{T}$, and then removing $\mathcal{T}$.

[13] Note that it is not our intention to provide optimised algorithms here, but just to convey the feasibility of this rewriting.

[14] A sequence of '{}'-delimited patterns in SPARQL corresponds to a join, where such joins can again be nested with UNIONs, with the obvious semantics, for details cf. [12].

Example 7. Getting back to the materialised version of the triple store G from Ex. 3, the update u from Ex. 4 would, according to $\mathbf{Sem}_2^{mat}$, be rewritten to

```
DELETE {?X a :Child. ?X :hasF ?x1. ?X :hasM ?x2. ?X :hasP ?x3.}
INSERT {?Y a :Mother. ?Y a :Parent. }
WHERE  {{?X :hasM ?Y.}    {?x1 a rdfs:Resource.
          ?x2 a rdfs:Resource.  ?x3 a rdfs:Resource.}}
```

with $G_u^{\mathbf{Sem}_2^{mat}}$ containing `:jane a :Mother, :Parent. :jack a :Parent.` ■

It is easy to argue that $\mathbf{Sem}_2^{mat}$ is mat-preserving. However, this semantics might still result in potentially non-intuitive behaviours. For instance, subsequent calls of INSERTs and DELETEs might leave "traces", as shown by the following example.

Example 8. Assume $G = O_{fam}$ from Ex. 1 with an empty ABox. Under $\mathbf{Sem}_2^{mat}$, the following sequence of updates would leave as a trace —among others— the resulting triples as in Ex. 7, which would not be the case under the naïve semantics.

```
DELETE{} INSERT {:joe :hasM :jane; :hasF :jack} WHERE{};
DELETE {:joe :hasM :jane; :hasF :jack} INSERT{} WHERE{}
```
■

$\mathbf{Sem}_3^{mat}$ tries to address the issue of such "traces", but can no longer be formulated by a relatively straightforward rewriting. For the present, preliminary paper we leave out a detailed definition/implementation capturing the intention of $\mathbf{Sem}_3^{mat}$; there are two possible starting points, namely combining $\mathbf{Sem}_{1a}^{mat} + \mathbf{Sem}_2^{mat}$, or $\mathbf{Sem}_{1b}^{mat} + \mathbf{Sem}_2^{mat}$, respectively. We emphasise though, that independently of this choice, a semantics that achieves the intention of $\mathbf{Sem}_3^{mat}$ would still potentially run into arguable cases, since it might run into removing seemingly "disconnected" implicit assertions, whenever removed assertions cause these, as shown by the following example.

Example 9. Assume a materialised triple store G consisting only of the TBox triples `:Father sc :Person, :Male .` The behaviour of the following update sequence under a semantics implementing the intention of $\mathbf{Sem}_3^{mat}$ is arguable:

```
DELETE {} INSERT {:x a :Father.} WHERE {};
DELETE {:x a :Male.} INSERT {} WHERE {}
```

We leave it open for now whether "recursive deletion of dangling effects" is intuitive: in this case, should upon deletion of x being Male, also be deleted that x is a Person? ■

In a strict reading of $\mathbf{Sem}_3^{mat}$'s intention, `:x a :Person.` would count as a dangling effect of the cause for `:x a :Male.`, since it is an effect of the inserted triple with no other causes in the store, and thus should be removed upon the delete operation.

Lastly, we point out that while implementations of (materialised) triple stores may make a distinction between implicit and explicitly inserted triples (e.g., by storing explicit and implicit triples separately, as sketched in $\mathbf{Sem}_{1b}^{mat}$ already), we consider the distinction between implicit triples and explicitly inserted ones non-trivial in the context of SPARQL 1.1 Update: for instance, is a triple inserted based upon implicit bindings in the WHERE clause of an INSERT statement to be considered "explicitly inserted" or not? We tend towards avoiding such distinction, but we have more in-depth discussions of such philosophical aspects of possible SPARQL update semantics on our agenda. For now, we turn our attention to the potential alternatives for red-preserving semantics.

5 Alternative Red-Preserving Semantics

Again, similar to $\mathbf{Sem}_3^{mat}$, for both baseline semantics $\mathbf{Sem}_0^{red}$ and $\mathbf{Sem}_1^{red}$ we leave it open whether they can be implemented by rewriting to SPARQL update operations following the naïve semantics, i.e., without the need to apply $red(G)$ over the whole triple store after each update; a strategy to avoid calling $red(G)$ would roughly include the following steps:

- delete the instantiations P_d *plus all the effects of instantiations* of P_i, which will be implied anyway upon the new insertion, thus preserving reduced;
- insert instantiations of P_i only if they are *not implied*, that is, they are not already implied by the current state of G or all their causes in G were to be deleted.

We leave further investigation of whether these steps can be cast into update requests directly by rewriting techniques to future work. Rather, we show that we can capture the intention of $\mathbf{Sem}_1^{red}$ by a straightforward extension of the baseline semantics.

Definition 11 ($\mathbf{Sem}_1^{red}$). *Let $u(P_d, P_i, P_w)$ be an update operation. Then*

$$G^{\mathbf{Sem}_1^{red}}_{u(P_d,P_i,P_w)} = red(G_{u(P_d^{caus},P_i,\{rewrite(P_w)\}\{P_d^{fvars}\})}),$$

where P_d^{caus} and P_d^{fvars} are as before.

Example 10. Getting back to the reduced version of the triple store G from Ex. 1, the update u from Ex. 4 would, according to $\mathbf{Sem}_1^{red}$, be rewritten to

```
DELETE { ?X a :Child. ?X :hasFather ?x1.
         ?X :hasMother ?x2. ?X :hasParent ?x3. }
INSERT { ?Y a :Mother. }
WHERE  { { ?X :hasMother ?Y. }
         { ?x1 a rdfs:Resource.
           ?x2 a rdfs:Resource.
           ?x3 a rdfs:Resource.} }
```

with $G_u^{\mathbf{Sem}_1^{red}}$ containing the triple `:jane a :Mother.`. Observe here the deletion of the triple `:joe :hasParent :jack.`, which some might view as non-intuitive. ■

In a reduced store effects of P_d need not be deleted, which makes the considerations that lead us to $\mathbf{Sem}_3^{mat}$ irrelevant for a red-preserving semantics, as shown next.

Example 11. Under $\mathbf{Sem}_1^{red}$, as opposed to $\mathbf{Sem}_2^{mat}$, the update sequence of Ex. 8 would leave no traces. However, the update sequence of Ex. 9 would likewise result in an empty ABox, again losing idempotence of single triple insertion followed by deletion. ■

Note that, while the rewriting for $\mathbf{Sem}_1^{red}$ is similar to that for $\mathbf{Sem}_2^{mat}$, post-processing for preserving reducedness is not available in off-the-shelf triple stores. Instead, $\mathbf{Sem}_2^{mat}$ could be readily executed by rewriting on existing triple stores, preserving materialisation.

6 TBox Updates

So far, we have considered the TBox as static. As already noted in [11], additionally allowing TBox updates considerably complicates issues and opens additional degrees of freedom for possible semantics. While it is out of the scope of this paper to explore all of these, we limit ourselves to sketch these different degrees of freedom and suggest one pragmatic approach to extend updates expressed in SPARQL to RDFS TBoxes.

In order to allow for TBox updates, we have to extend the update language: in the following, we will assume *general BGPs*, extending Def. 2.

Definition 12 (general BGP). *A* general BGP *is a set of triples of any of the forms from Table 1, where* $x, y, A, A', P, P' \in \Gamma \cup \mathcal{V}$.

We observe that with this relaxation for BGPs, updates as per Def. 3 can query TBox data, since they admit TBox triples in P_w. In order to address this issue we need to also generalise the definition of query answers.[15]

Definition 13. *Let* Q *be a union of general BGPs and* $[\![Q]\!]_G$ *the simple SPARQL semantics as per [21], i.e., essentially the set of query answers obtained as the union of answers from simple pattern matching of the general BGPs in* Q *over the graph* G*. Then we define* $ans_{\mathsf{RDFS}}(Q, G) = [\![Q]\!]_{mat(G)}$.

In fact, Def. 13 does not affect ABox inferences, that is, the following corollary follows immediately from Prop. 1 for non-general UCQs as per Def. 2.

Corollary 1. *Let Q be a UCQ as per Def. 2. Then* $ans_{\mathsf{RDFS}}(Q, G) = ans_{\mathsf{rdfs}}(Q, G)$.

As opposed to the setting discussed so far, where the last two rules in Fig. 1 used for TBox materialisation were ignored, we now focus on the discussion of terminological updates under the standard "intensional" semantics (essentially defined by the inference rules in Fig. 1) and attempt to define a reasonable (that means computable) semantics under this setting. Note that upon terminological queries, the RDFS semantics and DL semantics differ, since this "intensional" semantics does not cover all terminological inferences derivable in DL, cf. [7]; we leave the details of this aspect to future work.

Observation 1. TBox updates potentially affect both materialisation and reducedness of the ABox, that is, *(i)* upon TBox *insertions* a materialised ABox might need to be re-materialised in order to preserve materialisation, and, respectively, a reduced ABox might no longer be reduced; *(ii)* upon TBox *deletions* in a materialised setting, we have a similar issue to what we called "dangling" effects earlier, whereas in a reduced setting indirect deletions of implied triples could cause unintuitive behaviour.

Observation 2. Whereas deletions of implicit ABox triples can be achieved deterministically by deleting all single causes, TBox deletions involving `sc` and `sp` chains can be achieved in several distinct ways, as already observed by [11].

Example 12. Consider the graph $G = \{$`:A sc :B. :B sc :C. :B sc :D. :C sc :E. :D sc :E. :E sc :F.`$\}$ with the update `DELETE{:A sc :F.}`

Independent of whether we assume a materialised TBox, we would have various choices here to remove triples, to delete all the causes for `:A sc :F.` ■

[15] As mentioned in Fn. 8, elements of Γ may act as individuals, concept, or roles names in parallel.

In order to define a deterministic semantics for TBox updates, we need a canonical way to delete implicit and explicit TBox triples. Minimal cuts are suggested in [11] in the sc (or sp, resp.) graphs as candidates for deletions of sc (or sp, resp.) triples. However, as easily verified by Ex. 12, minimal multicuts are still ambiguous.

Here, we suggest two update semantics using rewritings to SPARQL 1.1 property path patterns [12] that yield canonical minimal cuts.

Definition 14. *Let $u(P_d, P_i, P_w)$ be an update operation where P_d, P_i, P_w are general BGPs. Then*

$$G^{\mathbf{Sem}^{mat}_{outcut}}_{u(P_d,P_i,P_w)} = mat(G_{u(P'_d,P_i,P'_w)}),$$

where each triple $\{A_1\ scp\ A_2\} \in P_d$ such that $scp \in \{\mathsf{sc}, \mathsf{sp}\}$ is replaced within P'_d by $\{A_1\ scp\ ?x.\}$, and we add to P'_w the property path pattern $\{A_1\ scp\ ?x.\ ?x\ scp^*\ A_2\}$. Analogously, $\mathbf{Sem}^{mat}_{incut}$ is defined by replacing $\{?x\ scp\ A_2\}$ within P'_d, and adding $\{A_1\ scp^*\ ?x.\ ?x\ scp\ A_2\}$ within P'_w instead.

Both $\mathbf{Sem}^{mat}_{outcut}$ and $\mathbf{Sem}^{mat}_{incut}$ may be viewed as straightforward extensions of $\mathbf{Sem}^{mat}_0$, i.e., both are mat-preserving and equivalent to the baseline semantics for non-general BGPs (i.e., on ABox updates):

Proposition 3. *Let $u(P_d, P_i, P_w)$ be an update operation, where P_d, P_i, P_w are (non-general) BGPs. Then*

$$G^{\mathbf{Sem}^{mat}_{outcut}}_{u(P_d,P_i,P_w)} \quad = \quad G^{\mathbf{Sem}^{mat}_{incut}}_{u(P_d,P_i,P_w)} \quad = \quad G^{\mathbf{Sem}^{mat}_{0}}_{u(P_d,P_i,P_w)}.$$

The intuition behind the rewriting in $\mathbf{Sem}^{mat}_{outcut}$ is to delete for every deleted $A\ scp\ B.$ triple, all directly outgoing scp edges from A that lead into paths to B, or, resp., in $\mathbf{Sem}^{mat}_{incut}$ all directly incoming edges to B. The intuition to choose these canonical minimal cuts is motivated by the following proposition.

Proposition 4. *Let $u =$ DELETE $\{A\ scp\ B\}$, and G a triple store with materialised TBox $\mathcal{T}$. Then, the TBox statements deleted by $G^{\mathbf{Sem}^{mat}_{outcut}}_{u(P_d,P_i,P_w)}$ (or, $G^{\mathbf{Sem}^{mat}_{incut}}_{u(P_d,P_i,P_w)}$, resp.) form a minimal cut [11] of $\mathcal{T}$ disconnecting A and B.*

Proof (Sketch). In a materialised TBox, one can reach B from A either directly or via n direct neighbours $C_i \neq B$, which (in)directly connect to B. So, a minimal cut contains either the multicut between A and the C_is, or between the C_is and B; the latter multicut requires at least the same amount of edges to be deleted as the former, which in turn corresponds to the outbound cut. This proves the claim for $\mathbf{Sem}^{mat}_{outcut}$. We can proceed analogously for $\mathbf{Sem}^{mat}_{incut}$. □

The following example illustrates that the generalisation of Prop. 4 to updates involving the deletion of several TBox statements at once does not hold.

Example 13. Assume the materialised triple store $G = \{$:A *scp* :B, :C, :D. :B *scp* :C, :D.$\}$ and $u =$ DELETE{:A *scp* :C. :A *scp* :D.}. Here, $\mathbf{Sem}^{mat}_{incut}$ does not yield a minimal *multicut* in G wrt disconnecting (:A, :C) and (:A, :D).[16] ■

As the example shows, the extension of the baseline ABox update semantics to TBox updates already yields new degrees of freedom. We leave a more in-depth discussion of TBox updates also extending the other semantics from Sec. 3 for future work.

[16] We can give an analogous example where $\mathbf{Sem}^{mat}_{outcut}$ does not yield a minimal multicut.

7 Prototype and Experiments

We have implemented the different update semantics discussed above in Jena TDB[17] as a triple store that both implements the latest SPARQL 1.1 specification and supports rule based materialisation: our focus here was to use an existing store that allows us to implement the different semantics with its on-board features; that is, for computing $mat(G)$ we use the on-board, forward-chaining materialisation in Jena.[18]

We have implemented all the above-mentioned mat-preserving semantics, with two concrete variants of P_d^{fvars}. In the first variant, we replace $?v$ a rdfs:Resource by `{{?v ?v_p ?v_o} UNION {?v_s ?v ?v_o} UNION {?v_s ?v_p ?v}}`, to achieve a pattern that binds $?v$ to every possible term in G. This is not very efficient. In fact, note that P_d^{fvars} is needed just to bind free variables $?v$ (corresponding to '_' in Table 2) in patterns $P_{?v}$ of the form $P(x, ?v)$ or $P(?v, x)$ in the rewritten DELETE clause. Thus, we can equally use $P_d^{fvars'} = \texttt{\{OPTIONAL\{}\bigcup_{?v \in Var(P_d^{caus}) \setminus Var(P_d)\}} P_{?v}\texttt{\}}$. We denote implementations using the latter variant $\mathbf{Sem}_{2'}^{mat}$ and $\mathbf{Sem}_{1'}^{red}$, respectively.

As for reduced semantics, remarkably, for the restricted set of ABox rules in Fig. 1 and assuming an acyclic TBox, we can actually compute $red(G)$ also by "on-board" means of SPARQL 1.1 compliant triple-stores, namely by using SPARQL 1.1 Update in combination with SPARQL 1.1 property paths [12, Section 9] with the following update:

```
DELETE  { ?S1 a ?D1. ?S2 a ?C2. ?S3 ?Q3 ?O3. ?O4 a ?C4. }
WHERE   {{ ?C1 sc+ ?D1. ?S1 a ?C1. }
   UNION { ?P2 dom/sc* ?C2. ?S2 ?P2 ?O2. }
   UNION { ?P3 sp+ ?Q3. ?S3 ?P3 ?O3. }
   UNION { ?P4 rng/sc* ?C4. ?S4 ?P4 ?O4. }}
```

We emphasise that performance results should be understood as providing a general indication of feasibility of implementing these semantics in existing stores rather than actual benchmarking: on the one hand, the different semantics are not comparable in terms of performance benchmarking, since they provide different results; on the other hand, for instance, we only use naive re-materialisation provided by the triple store in our prototype, instead of optimised versions of DRed, such as [26].

For initial experiments we have used data generated by the LUBM generator for 5, 10 and 15 Universities, which correspond to different ABox sizes merged together with an RDFS version of the LUBM ontology as TBox; this version of LUBM has no complex restrictions on roles, no transitive roles, no inverse roles, and no equality axioms, and axioms of type $A \sqsubseteq B \sqcap C$ are split into two axioms $A \sqsubseteq B$ and $A \sqsubseteq C$. Besides, we have designed a set of 7 different ABox updates in order to compare the proposed mat-preserving and red-preserving semantics. Both our prototype, as well as files containing the data, ontology, and the updates used for experiments are available on a dedicated Web page.[19]

We first compared, for each update semantics, the time elapsed for rewriting and executing the update. Secondly, in order to compare mat-preserving and red-preserving semantics, we also need to take into account that red-preserving semantics imply additional effort on subsequent querying, since rewriting is required (cf. Prop. 1). In order

[17] http://jena.apache.org/documentation/tdb/

[18] http://jena.apache.org/documentation/inference/

[19] http://dbai.tuwien.ac.at/user/ahmeti/sparqlupdate-rewriter/

to reflect this, we also measured the aggregated times for executing an update and subsequently processing the standard 14 LUBM benchmark queries in sequence.

Details of the results can be found on the above-mentioned Web page, we only provide a brief summary here: In general, among the mat-preserving semantics, the semantics implementable in terms of rewriting ($\mathbf{Sem}_{2}^{mat}$) perform better than those that need rematerialisation ($\mathbf{Sem}_{1a,b}^{mat}$), as could be expected. There might be potential for improvement here on the latter, when using tailored implementaions of DRed. Also, for both mat-preserving ($\mathbf{Sem}_{2'}^{mat}$) and red-preserving ($\mathbf{Sem}_{1'}^{red}$) semantics that rely on rewritings for deleting causes, the optimisation of using variant $P_d^{fvars'}$ instead of P_d^{fvars} paid off for our queries. As for a comparison between mat-preserving vs. red-preserving, in our experiments re-reduction upon updates seems quite affordable, whereas the additionally needed query rewriting for subsequent query answering does not add dramatic costs. Thus, we believe that, depending on the use case, keeping reduced stores upon updates is a feasible and potentially useful strategy, particularly since – as shown above – $red(G)$ can be implemented with off-the-shelf features of SPARQL 1.1.

While further optimisations, and implementations in different triple stores remain on our agenda, the experiments confirm our expectations so far.

8 Further Related Work and Possible Future Directions

Previous work on updates in the context of tractable ontology languages such as RDFS [11] and *DL-Lite* [5] typically has treated DELETEs and INSERTs in isolation, but not both at the same time nor in combination with templates filled by WHERE clauses, as in SPARQL 1.1; that is, these approaches are not based on BGP matching but rather on a set of ABox assertions to be updated, known a priori. Pairing both DELETE and INSERT, as in our case, poses new challenges, which we tried to address here in the practically relevant context of both materialised and reduced triple stores. In the future, we plan to extend our work in the context of *DL-Lite*, where we could build upon thoroughly studied query rewriting techniques (not necessarily relying on materialisation), and at the same time benefit from a more expressive ontology language. Expanding beyond our simple minimal RDFS language towards more features of *DL-Lite* or coverage of unrestricted RDF graphs would impose new challenges: for instance, consistency checking and consistency-preserving updates (as those treated in [5]), which do not yet play a role in the setting of RDFS, would become relevant; extensions in these directions, as well as practically evaluating the proposed semantics on existing triple stores is on our agenda.

As for further related works, in the context of reduced stores, we refer to [22], where the cost of redundancy elimination under various (rule-based) entailment regimes, including RDFS, is discussed in detail. In the area of database theory, there has been a lot of work on updating logical databases: Winslett [28] distinguishes between model-based and formula-based updates. Our approach clearly falls in the latter category; more concretely, ABox updates could be viewed as sets of propositional knowledge base updates [14] generated by SPARQL instantiating DELETE/INSERT templates. Let us further note that in the more applied area of databases, there are obvious parallels between some of our considerations and CASCADE DELETEs in SQL (that is, deletions under

foreign key constraints), in the sense that we trigger additional deletions of causes/effects in some of the proposed update semantics discussed herein.

9 Conclusions

We have presented possible semantics of SPARQL 1.1 Update in the context of RDFS. To the best of our knowledge, this is the first work to discuss how to combine RDFS with the new SPARQL 1.1 Update language. While we have been operating on a very restricted setting (only capturing minimal RDFS entailments, restricting BGPs to disallow non-standard use of the RDFS vocabulary), we could demonstrate that even in this setting the definition of a SPARQL 1.1 Update semantics under entailments is a non-trivial task. We proposed several possible semantics, neither of which might seem intuitive for all possible use cases; this suggests that there is no "one-size-fits-all" update semantics. Further, while ontologies should be "ready for evolution" [20], we believe that more work into semantics for updates of ontologies alongside with data (TBox & ABox) is still needed to ground research in *Ontology Evolution* into standards (SPARQL, RDF, RDFS, OWL), particularly in the light of the emerging importance of RDF and SPARQL in domains where data is continuously updated (dealing with dynamics in Linked Data, querying sensor data, or stream reasoning). We have taken a first step in this paper.

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Appendix

Algorithm 1: $rewrite(q, \mathcal{T})$

Input: Conjunctive query q, TBox $\mathcal{T}$
Output: Union (set) of conjunctive queries

```
1  P := {q}
2  repeat
3  |  P' := P
4  |  foreach q ∈ P' do
5  |  |  foreach g in q do    // expansion
6  |  |  |  foreach inclusion assertion I in T
   |  |  |  do
7  |  |  |  |  if I is applicable to g then
8  |  |  |  |  |  P := P ∪ {q[g/ gr(g, I)]}
9  until P' = P
10 return P
```

Table 2. Semantics of $\mathrm{gr}(g, I)$ in Alg.1

g	I	$\mathrm{gr}(g/I)$
$A(x)$	$A' \sqsubseteq A$	$A'(x)$
$A(x)$	$\exists P \sqsubseteq A$	$P(x, \_)$
$A(x)$	$\exists P^- \sqsubseteq A$	$P(\_, x)$
$P_1(x, y)$	$P_2 \sqsubseteq P_1$	$P_2(x, y)$

Here, '_' stands for a "fresh" variable.