Combining Rewriting and Incremental Materialisation Maintenance for Datalog Programs with Equality

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Abstract

Materialisation precomputes all consequences of a set of facts and a datalog program so that queries can be evaluated directly (i.e., independently from the program). *Rewriting* optimises materialisation for datalog programs with equality by replacing all equal constants with a single representative; and *incremental maintenance* algorithms can efficiently update a materialisation for small changes in the input facts. Both techniques are critical to practical applicability of datalog systems; however, we are unaware of an approach that combines rewriting and incremental maintenance. In this paper we present the first such combination, and we show empirically that it can speed up updates by several orders of magnitude compared to using either rewriting or incremental maintenance in isolation.

1 Introduction

Datalog [Abiteboul *et al.*, 1995] is a declarative, rule-based language capable of describing (possibly recursive) data dependencies. It is widely used in applications as diverse as enterprise data management [Aref, 2010] and query answering over ontologies in the OWL 2 RL profile [Motik *et al.*, 2009] extended with SWRL rules [Horrocks *et al.*, 2004].

Querying the set $\Pi^\infty(E)$ of consequences of a set of *explicit* facts E and a datalog program Π is the key service of datalog systems. It is often supported by precomputing and storing $\Pi^\infty(E)$ so that queries can be evaluated directly, without further reference to Π. Set $\Pi^\infty(E)$ and the process of computing it are called the *materialisation* of E w.r.t. Π. State of the art systems such as Olwgres [Stocker and Smith, 2008], WebPIE [Urbani *et al.*, 2012], Oracle's RDF store [Wu *et al.*, 2008], GraphDB (formerly OWLIM) [Bishop *et al.*, 2011], and RDFox [Motik *et al.*, 2014] implement this technique.

Although datalog traditionally employs the unique name assumption (UNA), in some applications uniqueness of identifiers cannot be guaranteed (e.g., in the Semantic Web, due to the distribution and the independence of data sources). Such applications require an extension of datalog without UNA, in which one can infer equalities between constants using a special *equality* predicate $\approx$ that can occur in rule heads and facts. The semantics of $\approx$ can be captured explicitly using rules that *axiomatise* $\approx$ as a congruence relation; however, this is known to be inefficient when equality is used extensively. Therefore, systems commonly use *rewriting* [Baader and Nipkow, 1998; Nieuwenhuis and Rubio, 2001]—an optimisation where equal constants are replaced with a canonical *representative*, and only facts containing such representatives are stored. The benefits of rewriting have been well-documented in practice [Wu *et al.*, 2008; Urbani *et al.*, 2012; Bishop *et al.*, 2011; Motik *et al.*, 2015a].

Moreover, datalog applications often need to handle continuous updates to the set of explicit facts E. *Rematerialisation* (i.e., computing the materialisation from scratch) is often very costly. An alternative is to use an *incremental maintenance* algorithm. Adding facts to E is trivial as one can simply continue from where the initial materialisation has finished; hence, given a materialisation $\Pi^\infty(E)$ of E w.r.t. Π and a set of facts E^-, the main challenge for an incremental algorithm is to efficiently compute $\Pi^\infty(E \setminus E^-)$. Several such algorithms have already been proposed. *Counting* [Nicolas and Yazdanian, 1983; Gupta *et al.*, 1993; Urbani *et al.*, 2013] stores the number of derivations for each fact in $\Pi^\infty(E)$ during initial materialisation, and it uses this number to determine when to delete a fact from $\Pi^\infty(E)$; however, counting works correctly only with nonrecursive rules, and a proposed extension to recursive rules requires multiple counts per fact [Dewan *et al.*, 1992]. The *Delete/Rederive* (DRed) algorithm [Gupta *et al.*, 1993] handles recursive rules with no storage overhead: to delete E^- from E, the algorithm first overdeletes all consequences of E^- in $\Pi^\infty(E)$ and then rederives all facts provable from $E \setminus E^-$. The *Backward/Forward* (B/F) algorithm combines backward and forward chaining in a way that outperforms DRed on inputs where facts have many alternative derivations, a common scenario in Semantic Web applications [Motik *et al.*, 2015b].

Unfortunately, combining rewriting and incremental maintenance is difficult due to complex interactions between the two: removing E^- from E may entail retracting equalities, which may (partially) invalidate the rewriting and require the restoration of rewritten facts (see Section 3). To the best of our knowledge, such a combination has not been considered in the literature, and practical systems either use rewriting with rematerialisation, or axiomatise equality and use incremental maintenance; in either case they give up a technique known to be critical for performance. In this paper we present the B/F$^{\approx}$ algorithm, which combines rewriting with B/F: given a set of facts E^-, our algorithm efficiently updates the materialisation of E w.r.t. Π computed using the rewriting approach by Motik *et al.* (2015a). Extensions of datalog with equality are nowadays used mainly for querying RDF data extended with OWL 2 RL ontologies and SWRL rules, so we formalise our algorithm in the framework of RDF; however, our approach can easily be adapted to general datalog.

We have implemented B/F$^{\approx}$ in the open-source RDFox system[1] and have evaluated it on several real-world and synthetic datasets. Our results show that the algorithm indeed combines the best of both worlds, as it is often several orders of magnitude faster than either rematerialisation with rewriting, or B/F with axiomatised equality.

2 Preliminaries

Datalog. A *term* is a *constant* (a, b, A, R, etc.) or a variable (x, y, z, etc.). An *(RDF) atom* has the form $\langle t_1, t_2, t_3 \rangle$, where t_1, t_2, t_3 are terms; an *(RDF) fact* (also called a *triple*) is a variable-free RDF atom; and a *dataset* is a finite set of facts. A *(datalog) rule* r is an implication of the form (1), where $H, B_1, \ldots, B_n$ are atoms and each variable occurring in H also occurs in some B_i; $\mathsf{h}(r) := H$ is the *head atom* of r; each B_i is a *body atom* of r; and $\mathsf{b}(r)$ is the set of all body atoms of r. A *(datalog) program* is a finite set of rules.

$$H \leftarrow B_1 \wedge \cdots \wedge B_n \tag{1}$$

A *substitution* is a partial mapping of variables to terms. For α a term, atom, rule, or a set of these, $\mathsf{voc}(\alpha)$ is the set of all constants in α, and $\alpha\sigma$ is the result of applying a substitution σ to α. The *materialisation* $\Pi^\infty(E)$ of a dataset E w.r.t. a program Π is the smallest superset of E containing $\mathsf{h}(r)\sigma$ for each rule $r \in \Pi$ and substitution σ with $\mathsf{b}(r)\sigma \subseteq \Pi^\infty(E)$.

Equality. The constant *owl:sameAs* (abbreviated $\approx$) can be used to encode equality between constants. For example, fact $\langle \mathsf{P.\_Smith}, \approx, \mathsf{Peter\_Smith} \rangle$ states that $\mathsf{P.\_Smith}$ and $\mathsf{Peter\_Smith}$ are one and the same object. Facts of the form $\langle s, \approx, t \rangle$ are called *equalities* and, for readability, are abbreviated as $s \approx t$; note that $\approx \in \mathsf{voc}(s \approx t)$. Program $\Pi_\approx$ consisting of rules ($\approx_1$)–($\approx_4$) axiomatises $\approx$ as a congruence relation. If a program Π or a dataset E contain $\approx$, systems then answer queries in the materialisation of E w.r.t. $\Pi \cup \Pi_\approx$.

$$\langle x_1', x_2, x_3 \rangle \leftarrow \langle x_1, x_2, x_3 \rangle \wedge x_1 \approx x_1' \tag{$\approx_1$}$$

$$\langle x_1, x_2', x_3 \rangle \leftarrow \langle x_1, x_2, x_3 \rangle \wedge x_2 \approx x_2' \tag{$\approx_2$}$$

$$\langle x_1, x_2, x_3' \rangle \leftarrow \langle x_1, x_2, x_3 \rangle \wedge x_3 \approx x_3' \tag{$\approx_3$}$$

$$x_i \approx x_i \leftarrow \langle x_1, x_2, x_3 \rangle, \text{for } 1 \le i \le 3 \tag{$\approx_4$}$$

Rewriting is a well-known optimisation of this approach. For π a mapping of constants to constants and α a constant, fact, rule, dataset, or substitution, $\pi(\alpha)$ is the result of replacing each constant c in α with $\pi(c)$; such α is *normal* w.r.t. π if $\pi(\alpha) = \alpha$; and $\pi(\alpha)$ is the *representative* of α in π. For c a constant, let $c^\pi := \{d \mid \pi(d) = c\}$. For U a dataset, let $U^\pi := \{\langle s, p, o \rangle \mid \langle \pi(s), \pi(p), \pi(o) \rangle \in U\}$; and, for F a fact, let $F^\pi := \{F\}^\pi$. We assume that all constant are totally ordered such that $\approx$ is the smallest constant; then, for S a nonempty set of constants, $\min S$ (resp. $\max S$) is the smallest (resp. greatest) element of S. Let U be a dataset and let $\mathsf{E}_c(U) := \{c\} \cup \{d \mid c \approx d \in U\}$; then, the *rewriting* of U is the pair (π, I) such that

1. $\pi(c) = \min \mathsf{E}_c(U)$ for each constant c, and
2. $I = \pi(U)$.

Note that $\pi(\approx) = \approx$, that the rewriting is unique for U, and that $\Pi_\approx^\infty(U) = U$ implies $I^\pi = U$. The *r-materialisation* of a dataset E w.r.t. a program Π is the rewriting (π, I) of the dataset $J = (\Pi \cup \Pi_\approx)^\infty(E)$. Motik *et al.* (2015a) show how to answer queries over J by materialising (π, I) instead of J.

3 Updating R-Materialisation Incrementally

Let E and E^- be datasets, let $E' = E \setminus E^-$, and let Π be a program. Moreover, let J (resp. J') be the materialisation of E (resp. E') w.r.t. $\Pi \cup \Pi_\approx$, and let (π, I) (resp. (π', I')) be the r-materialisation of E (resp. E') w.r.t. Π. Given (π, I), Π, and E^-, the B/F$^{\approx}$ algorithm computes (π', I') efficiently by combining the B/F algorithm by Motik *et al.* (2015b) for incremental maintenance in datalog without equality with the r-materialisation algorithm by Motik *et al.* (2015a). We discuss the intuition in Section 3.1 and some optimisations in Section 3.2, and we formalise the algorithm in Section 3.3.

3.1 Intuition

Main Difficulty. An update may lead to the deletion of equalities, which may require *adding* facts to I. Consider the following example:

$$\begin{aligned}
\Pi = \{\, & y_1 \approx y_2 \leftarrow \langle y_1, \mathsf{R}, x \rangle \wedge \langle y_2, \mathsf{R}, x \rangle, \\
& y_1 \approx y_2 \leftarrow \langle x, \mathsf{R}, y_1 \rangle \wedge \langle x, \mathsf{R}, y_2 \rangle \,\}
\end{aligned}$$

$$\begin{aligned}
E &= \{\, \langle \mathsf{a}, \mathsf{R}, \mathsf{b} \rangle,\ \langle \mathsf{c}, \mathsf{R}, \mathsf{d} \rangle,\ \langle \mathsf{a}, \mathsf{R}, \mathsf{d} \rangle \,\} \\
I &= \{\, \langle \mathsf{a}, \mathsf{R}, \mathsf{b} \rangle,\ \mathsf{a} \approx \mathsf{a},\ \mathsf{R} \approx \mathsf{R},\ \mathsf{b} \approx \mathsf{b},\ \approx \approx \approx \,\} \\
\pi &= \{\, \mathsf{a} \mapsto \mathsf{a},\ \mathsf{b} \mapsto \mathsf{b},\ \mathsf{c} \mapsto \mathsf{a},\ \mathsf{d} \mapsto \mathsf{b},\ \mathsf{R} \mapsto \mathsf{R},\ \approx \mapsto \approx \,\}
\end{aligned}$$

$$\begin{aligned}
E^- &= \{\, \langle \mathsf{a}, \mathsf{R}, \mathsf{d} \rangle \,\} \\
I' &= \{\, \langle \mathsf{a}, \mathsf{R}, \mathsf{b} \rangle,\ \mathsf{a} \approx \mathsf{a},\ \mathsf{R} \approx \mathsf{R},\ \mathsf{b} \approx \mathsf{b},\ \approx \approx \approx, \\
& \qquad \langle \mathsf{c}, \mathsf{R}, \mathsf{d} \rangle,\ \mathsf{c} \approx \mathsf{c},\ \mathsf{d} \approx \mathsf{d} \,\} \\
\pi' &= \{\, \mathsf{a} \mapsto \mathsf{a},\ \mathsf{b} \mapsto \mathsf{b},\ \mathsf{c} \mapsto \mathsf{c},\ \mathsf{d} \mapsto \mathsf{d},\ \mathsf{R} \mapsto \mathsf{R},\ \approx \mapsto \approx \,\}
\end{aligned}$$

Relation R is bijective in Π, so $\mathsf{a} \approx \mathsf{c} \in J$ as both a and c have outgoing R-edges to d, and $\mathsf{b} \approx \mathsf{d} \in J$ as both b and d have incoming R-edges from a. By rewriting, we represent each fact $\langle \alpha, \mathsf{R}, \beta \rangle$ from J using a single fact $\langle \mathsf{a}, \mathsf{R}, \mathsf{b} \rangle$, and analogously for facts involving $\approx$; thus, instead of 14 facts, we store just five facts. Assume now that we remove E^- from E. In J and J' we ascribe no particular meaning to $\approx$, so the monotonicity of datalog ensures $J \subseteq J'$; thus, the B/F algorithm just needs to delete facts that no longer hold. However, $\mathsf{a} \approx \mathsf{c} \notin J'$ and $\mathsf{b} \approx \mathsf{d} \notin J'$, so we must update π and extend I with the facts from J' that are not represented via π'. Thus, in our example, I' actually *contains* I.

Solution Overview. B/F$^{\approx}$ consists of Algorithms 1–7 that follow the same basic idea as B/F; to highlight the differences, lines that exist in B/F in a modified form are marked with '$*$', and new lines and algorithms are marked with '$\triangleright$'.

[1] http://www.cs.ox.ac.uk/isg/tools/RDFox/

We initially mark all facts in $\pi(E^-)$ as 'doubtful'—that is, we indicate that their truth might change. Next, for each 'doubtful' fact F, we determine whether F is provable from E' and, if not, we identify the immediate consequences of F (i.e., the facts in I that can be derived using F) and mark them as 'doubtful'. After processing all 'doubtful' facts we know exactly which facts have changed, so we can update I. To check the provability of F, we use backward chaining to identify the facts in I that can prove F, and we use forward chaining to actually prove F. The latter process is structured to keep track of the necessary changes to π and I. We next describe the components of B/F$^{\approx}$ in more detail.

Procedure $\mathsf{saturate}()$ is given a dataset $C \subseteq I$ of *checked* facts, and it computes the set L containing each fact F derivable from E' such that each fact in a derivation of F is contained in C^π; thus, C identifies the part of J' to recompute. Rather than storing L directly, we adapt the r-materialisation algorithm by Motik *et al.* (2015a) and represent L by its rewriting $(\gamma, P \setminus \hat{P})$; the role of the two sets P and $\hat{P}$ is discussed shortly. Lines 36–40 compute the facts in L derivable immediately from E': we iterate over each $F \in C$ and each $G \in F^\pi$; since we represent L by its rewriting, we add $\gamma(G)$ to P. The roles of set Y and lines 37–39 will be discussed shortly. Lines 41–50 compute the facts in L derivable using rules: we consider each fact F in $P \setminus \hat{P}$ (lines 41–42), each rule r, and each match σ of F to a body atom of r (line 48), we evaluate the remaining body atoms of r (line 49), and we derive $\gamma(\mathsf{h}(r)\tau)$ for each match τ (line 50). This basic idea is slightly more complicated due to rewriting: if $F = a \approx b$, we modify γ so that one constant becomes the representative of the other (line 45). As a consequence, facts can become 'outdated' w.r.t. γ, so we keep track of such facts using $\hat{P}$: if F is 'outdated', we add F to $\hat{P}$ and $\gamma(F)$ to P (line 44); due to the latter, $P \setminus \hat{P}$ eventually contains all 'up to date' facts. Finally, we apply the reflexivity rules ($\approx_4$) to F (line 47).

Procedure $\mathsf{saturate}()$ is repeatedly called in B/F$^{\approx}$. Set C, however, never shrinks between successive calls, so set L never shrinks either; hence, at each call we can just continue the computation instead of starting 'from scratch'. A minor problem arises if we derive a fact F with $F \notin C^\pi$ and so we do not add $\gamma(F)$ to P, but C is later extended so that $F \in C^\pi$ holds. We handle this by maintaining a set Y of 'delayed' facts: in line 59 we add F to Y if $F \notin C^\pi$; and in line 40 we identify each 'delayed' fact $G \in C^\pi \cap Y$ and add $\gamma(G)$ to P.

Procedure $\mathsf{rewrite}(a, b)$ implements rewriting: we update γ (line 52), apply the replacement rules ($\approx_1$)–($\approx_3$) to already processed facts containing 'outdated' constants (line 54), ensure that Γ is normal w.r.t. γ (line 56), and reapply the normalised rules (lines 57–58). Motik *et al.* (2015a) discuss in detail the issues related to rule updating and reevaluation.

Procedure $\mathsf{checkProvability}()$ takes a fact $F \in I$ and ensures that, for each $G \in F^\pi$, we have $G \in J'$ iff $\gamma(G) \in P \setminus \hat{P}$—that is, we know the correct status of each fact that F represents. To this end, we add F to C (line 22) and to ensure that $(\gamma, P \setminus \hat{P})$ correctly represents L (line 23). Each fact is added to C only once, which guarantees termination of the recursion. We then use backward chaining to examine facts occurring in proofs of F and recursively check their provability; we stop at any point during that process if all facts in F^π become provable (lines 24, 28, 31, and 35). Lines 25–24 handle the reflexivity rules ($\approx_4$): to check provability of $c \approx c$, we recursively check the provability each fact containing c. Lines 29–31 handle replacement rules ($\approx_1$)–($\approx_3$): we recursively check the provability of $c \approx c$ for each constant c occurring in F. Finally, lines 32–35 handle the rules in $\pi(\Pi)$: we consider each rule $r \in \pi(\Pi)$ whose head matches F and each substitution τ that matches the body of r in I, and we recursively check the provability of $\mathsf{b}(r)\tau$.

Procedure $\mathsf{BF}^{\approx}()$ computes the set $D \subseteq I$ of 'doubtful' facts. After initialising D to $\pi(E^-)$ (lines 3–4), we consider each fact $F \in D$ (lines 5–16) and determine whether some $G \in F^\pi$ is no longer provable (line 6); if so, we add to D all facts that might be affected by the deletion of G. Lines 9–11 handle rules ($\approx_1$)–($\approx_3$); line 12 handles rules ($\approx_4$); and lines 13–15 handle $\pi(\Pi)$: we identify each rule $r \in \pi(\Pi)$ where F matches a body atom of r, we evaluate the remaining body atoms of r in I, and we add $\mathsf{h}(r)\tau$ to D for each τ such that $\mathsf{b}(r)\tau \subseteq I$. With D processed, $(\gamma, P \setminus \hat{P})$ reflects the changes to (π, I), which we exploit in Algorithm 2.

3.2 Optimisations

Reflexivity. Facts of the form $F = c \approx c$ can be expensive for backward chaining: due to reflexivity rules ($\approx_4$), in lines 25–28 we may end up recursively proving each fact G that mentions c. However, F holds trivially if E' contains a fact mentioning c, in which case we can consider F proven and avoid any recursion. This is implemented in lines 37–39.

Avoiding Redundant Derivations. Assume that Γ contains a rule $y_1 \approx y_2 \leftarrow \langle x, \mathsf{R}, y_1 \rangle \wedge \langle x, \mathsf{R}, y_2 \rangle$, and consider a call to $\mathsf{saturate}()$ in which facts $\langle a, R, b \rangle$ and $\langle a, R, d \rangle$ both end up in P. Unless we are careful, in line 50 we might consider substitution $\tau_1 = \{x \mapsto a,\ y_1 \mapsto b,\ y_2 \mapsto d\}$ twice: once when we match $\langle a, R, b \rangle$ to $\langle x, \mathsf{R}, y_1 \rangle$, and once when we match $\langle a, R, d \rangle$ to $\langle x, \mathsf{R}, y_2 \rangle$. Such redundant derivations can substantially degrade performance.

To solve this problem, set V keeps track of the processed subset of P: after we extract a fact F from P, in line 42 we transfer F to V; moreover, in line 49 we evaluate rule bodies in $V \setminus \hat{P}$ instead of $P \setminus \hat{P}$. Now if $\langle a, R, b \rangle$ is processed before $\langle a, R, d \rangle$, at that point we have $\langle a, R, d \rangle \notin V$, so τ_1 is not returned as a match in line 49; the situation when $\langle a, R, d \rangle$ is processed first is analogous. This, however, does not eliminate all repetition: $\tau_2 = \{x \mapsto a, y_1 \mapsto b, y_2 \mapsto b\}$ is still considered when $\langle a, R, b \rangle$ is matched to either of the two body atoms in the rule. Therefore, we annotate (see Section 3.3) the body atoms of rules so that, whenever F is matched to some body atom B_i, no atom B_j preceding B_i in the body of r can be matched to F. In our example, τ_2 is thus considered only when $\langle a, R, b \rangle$ is matched to $\langle x, \mathsf{R}, y_1 \rangle$.

B/F$^{\approx}$ avoids redundant derivations in similar vein: set O tracks the processed subset of D; in lines 10 and 14 we match the relevant rules in $I \setminus O$; and in line 16 we add a fact to O once it has been processed.

Disproved Facts. For each $F \in I$ with $F^\pi \cap J' = \emptyset$, no fact in F^π participates in a proof of any fact in J'. Thus, in line 7 we collect all such facts in a set S of *disproved* facts, and in lines 26, 29, and 33 we exclude S from backward chaining.

Singletons. If we encounter $F = c \approx c$ in line 9 or 29 where c is only the representative of itself (i.e., $|c^\pi| = 1$), then we know that no fact in F^π can derive a new fact using rules $(\approx_1)$–$(\approx_3)$, and so we can avoid considering such rules.

3.3 Formalisation

We borrow the notation by Motik *et al.* (2015b) to formalise B/F$^\approx$. We recapitulate some definitions, present the pseudocode, and formally state the algorithm's properties.

Given a dataset X and a fact F, operation $X.\mathsf{add}(F)$ adds F to X, and operation $X.\mathsf{delete}(F)$ removes F from X; both return $\mathtt{t}$ if X was changed. For iteration, operation $X.\mathsf{next}$ returns the next fact from X, or ε if no such fact exists.

An *annotated query* has the form $Q = B_1^{\bowtie_1} \wedge \dots \wedge B_k^{\bowtie_k}$, where each B_i is an atom and *annotation* $\bowtie_i$ is either empty or equal to $\neq$. Given datasets X and Y and a substitution σ, operation $X.\mathsf{eval}(Q, Y, \sigma)$ returns a set containing each smallest substitution τ such that $\sigma \subseteq \tau$ and, for $1 \le i \le k$, (i) $B_i\tau \in X$ if $\bowtie_i$ is empty or (ii) $B_i\tau \in X \setminus Y$ if $\bowtie_i$ is $\neq$. We often write $[Z \setminus W]$ instead of X, meaning that Q is evaluated in the difference of sets Z and W.

Given a fact F, operation $\Pi.\mathsf{matchHead}(F)$ returns all tuples $\langle r, Q, \sigma\rangle$ with $r \in \Pi$ a rule of the form (1), σ a substitution such that $H\sigma = F$, and $Q = B_1 \wedge \dots \wedge B_n$. Moreover, operation $\Pi.\mathsf{matchBody}(F)$ returns all tuples $\langle r, Q, \sigma\rangle$ with $r \in \Pi$ a rule of the form (1), σ a substitution such that $B_i\sigma = F$ for some $1 \le i \le n$, and

$$Q = B_1^{\neq} \wedge \dots \wedge B_{i-1}^{\neq} \wedge B_{i+1} \wedge \dots \wedge B_n. \quad (2)$$

Finally, given a mapping γ of constants to constants, and constants d and c, operation $\gamma.\mathsf{mergeInto}(d, c)$ modifies γ so that $\gamma(e) = c$ holds for each constant e with $\gamma(e) = d$.

B/F$^\approx$ consists of Algorithms 1–7. Theorem 1 shows that the algorithm is correct and that, just like the seminaïve algorithm [Abiteboul *et al.*, 1995], it does not repeat derivations; the proof is given in the appendix.

4 Evaluation

We have implemented and evaluated the B/F$^\approx$ algorithm using the open-source RDF data management system RDFox.[2] The system and the test data are all available online.[3]

Objectives. Updates can be handled either incrementally or by rematerialisation, and equality can be handled either by rewriting or by axiomatisation, giving rise to four possible approaches to updates. Our first objective was to compare all of them to determine their relative strengths and weaknesses.

As E^- increases in size, incremental update becomes harder, but rematerialisation becomes easier. Our second objective was to investigate the relationship between the update size and the performance of the respective approaches.

Datasets. Equality is often used in OWL ontologies on the Semantic Web, so we based our evaluation on several well-known synthetic and 'real' RDF datasets.

Each dataset comprises an OWL ontology and a set of explicit facts E. *UOBM* [Ma *et al.*, 2006] extends LUBM [Guo *et al.*, 2005], and we used the data generated for 100 universities; we did not use LUBM because it does not use $\approx$. *Claros* records information on cultural artefacts.[4] *DBpedia* consists of structured information extracted from Wikipedia.[5] *UniProt* is a knowledge base about protein sequences;[6] we selected a subset of the original (very large) set of facts. Finally, *OpenCyc* is an extensive, manually curated upper ontology.[7]

We followed Zhou *et al.* (2013) to convert the ontologies into *lower* (**L**) and *upper bound* (**U**) programs: the former captures the OWL 2 RL subset of the ontology transformed into datalog as described by Grosof *et al.* (2003), and the latter captures all consequences of the ontology using an unsound approximation. Upper bound programs are interesting since their rules tend to be highly connected. Moreover, we manually extended the lower bound (**LE**) of Claros with 'hard' rules (e.g., we defined related documents as pairs of documents that refer to the same topic).

Update Sets. For each dataset, we randomly selected several subsets E^- of E. We considered small updates of 100 and 5k facts on all datasets. Moreover, for each dataset we identified the 'equilibrium' point n at which B/F$^\approx$ and Remat$^\approx$ take roughly the same time. If n was large, we generated subsets E^- with sizes equal to 25%, 50%, 75%, and 100% of n; otherwise, we divided n in an ad hoc way.

Test Setting. We conducted our experiments on a server with 256 GB of RAM and two Intel Xeon E5-2670 CPUs at 2.60GHz running Fedora release 20, kernel version 3.17.7-200.fc20.x86_64. Since RDFox runs in main memory, we did not consider cold and warm runs.

Test Results. Table 1 summarises our test results. For each dataset, $|E|$ and $|\Pi|$ show the numbers of explicit facts and rules; $|I^\approx|$, $T^\approx$, and $D^\approx$ show the number of facts in the initial materialisation, and the time and the number of derivations used to compute it via rewriting; and $|I^A|$, T^A, and D^A show the same for the initial materialisation with axiomatised equality. For each set E^-, we show the numbers $\Delta|I^\approx|$ and $\Delta|I^A|$ of deleted facts with rewriting and axiomatisation, respectively, as well as the times (T) and the number of derivations (D) for each of the four update approaches. All times are in seconds. In B/F$^\approx$, each D is the sum of the number of times a fact is made 'doubtful' (lines 11, 12, and 15), checked in backward chaining (lines 27, 30, and 34), or derived in forward chaining (line 59), and we use it to estimate reasoning difficulty independently from implementation details. We could not complete all axiomatisation tests with Claros-LE as each run took more than two hours to complete; we marked the corresponding entries as —.

Discussion. For updates of 100 facts, B/F$^\approx$ outperforms all other approaches, often by orders of magnitude, and in most cases it does so even for much larger updates.

Even when $|I^A| - |I^\approx|$ is 'small' (i.e., when not many

[2]http://www.cs.ox.ac.uk/isg/tools/RDFox/

[3]http://tinyurl.com/qh6ztg6

[4]http://www.clarosnet.org/XDB/ASP/clarosHome/

[5]http://dbpedia.org/

[6]http://www.uniprot.org

[7]http://www.cyc.com/platform/opencyc

Input Variables

E	: explicit facts
Π	: the datalog program
(π, I)	: the r-materialisation of E w.r.t. Π
E^-	: facts to delete from E

Global Temporary Variables

D	: consequences of E^- that might need to be deleted
O	: the processed subset of D
C	: facts whose provability must be checked
γ	: mapping recording the changes needed to π
P	: proved facts
$\hat{P}$	: proved rewritten facts
Y	: proved facts not in C^π
V	: the processed subset of P
S	: the set of disproved facts

Algorithm 1 $\mathsf{B/F}^{\approx}()$

$*$ 1: $C := D := P := \hat{P} := Y := O := S := V := \emptyset$
$\triangleright$ 2: initialise γ as identity and $\Gamma := \Pi$
3: **for each** $F \in E^-$ **do**
4:     **if** $E.\mathsf{delete}(F)$ **then** $D.\mathsf{add}(\pi(F))$
5: **while** $(F := D.\mathsf{next}) \neq \varepsilon$ **do**
6:     $\mathsf{checkProvability}(F)$
$*$ 7:   **for each** $G \in C$ s.t. $\mathsf{allDisproved}(G)$ **do** $S.\mathsf{add}(G)$
$*$ 8:   **if** not $\mathsf{allProved}(F)$ **then**
$\triangleright$ 9:   **if** $F = c \approx c$ and $|c^\pi| > 1$ **then**
$\triangleright$10:   **for each** $G \in I \setminus O$ with $c \in \mathsf{voc}(G)$ **do**
$\triangleright$11: $D.\mathsf{add}(G)$
$\triangleright$12:   **for each** $c \in \mathsf{voc}(F)$ **do** $D.\mathsf{add}(c \approx c)$
13:         **for each** $\langle r, Q, \sigma \rangle \in \pi(\Pi).\mathsf{matchBody}(F)$ **do**
14:             **for each** $\tau \in [I \setminus O].\mathsf{eval}(Q, \{F\}, \sigma)$ **do**
15:                 $D.\mathsf{add}(\mathsf{h}(r)\tau)$
16:         $O.\mathsf{add}(F)$
$*$17: $\mathsf{propagateChanges}()$

$\triangleright$ **Algorithm 2** $\mathsf{propagateChanges}()$

18: **for each** $c \approx c \in C$ and each d with $\pi(d) = c$ **do**
19:     $\pi(d) := \gamma(d)$
20: **for each** $F \in D \setminus (P \setminus \hat{P})$ **do** $I.\mathsf{delete}(F)$
21: **for each** $F \in P \setminus \hat{P}$ **do** $I.\mathsf{add}(\pi(F))$

$\triangleright$ **Algorithm 3** Auxiliary functions

$\mathsf{allProved}(F)$:
    t iff $F \notin S$ and $\gamma(F^\pi) \subseteq (P \setminus \hat{P})$
$\mathsf{allDisproved}(F)$:
    t iff $\gamma(F^\pi) \cap (P \setminus \hat{P}) = \emptyset$

Algorithm 4 $\mathsf{checkProvability}(F)$

22: **if** not $C.\mathsf{add}(F)$ **then return**
23: $\mathsf{saturate}()$
$*$24: **if** $\mathsf{allProved}(F)$ **then return**
$\triangleright$25: **if** $F = c \approx c$ **then**
$\triangleright$26:   **for each** $G \in I \setminus S$ with $c \in \mathsf{voc}(G)$ **do**
$\triangleright$27: $\mathsf{checkProvability}(G)$
$\triangleright$28:   **if** $\mathsf{allProved}(F)$ **then return**
$\triangleright$29: **for each** $c \in \mathsf{voc}(F)$ with $c \approx c \notin S$ and $|c^\pi| > 1$ **do**
$\triangleright$30: $\mathsf{checkProvability}(c \approx c)$
$\triangleright$31:   **if** $\mathsf{allProved}(F)$ **then return**
32: **for each** $\langle r, Q, \sigma \rangle \in \pi(\Pi).\mathsf{matchHead}(F)$ **do**
33:     **for each** $\tau \in [I \setminus S].\mathsf{eval}(Q, \emptyset, \sigma)$ and $G \in \mathsf{b}(r)\tau$ **do**
34:         $\mathsf{checkProvability}(G)$
35:         **if** $\mathsf{allProved}(F)$ **then return**

Algorithm 5 $\mathsf{saturate}()$

36: **while** $(F := C.\mathsf{next}) \neq \varepsilon$ **do**
$\triangleright$37:   **if** $F = c \approx c$ **then**
$\triangleright$38:   **for each** $d \in \mathsf{voc}(E)$ with $\pi(d) = c$ **do**
$\triangleright$39: $P.\mathsf{add}(\gamma(d) \approx \gamma(d))$
$*$40:   **for each** $G \in F^\pi \cap (E \cup Y)$ **do** $P.\mathsf{add}(\gamma(G))$
41: **while** $(F := P.\mathsf{next}) \neq \varepsilon$ **do**
$*$42:   **if** $F \in P \setminus (\hat{P} \cup V)$ and $V.\mathsf{add}(F)$ **then**
$\triangleright$43: $G := \gamma(F)$
$\triangleright$44:   **if** $F \neq G$ **then** $\hat{P}.\mathsf{add}(F)$ and $P.\mathsf{add}(G)$
$\triangleright$45:   **else if** $F = a \approx b$ and $a \neq b$ **then** $\mathsf{rewrite}(a, b)$
$\triangleright$46:   **else**
$*$47:   **for each** $c \in \mathsf{voc}(G)$ **do** $\mathsf{prove}(c \approx c)$
48:             **for each** $\langle r, Q, \sigma \rangle \in \Gamma.\mathsf{matchBody}(G)$ **do**
$*$49:   **for each** $\tau \in [V \setminus \hat{P}].\mathsf{eval}(Q, \{G\}, \sigma)$ **do**
$*$50: $\mathsf{prove}(\mathsf{h}(r)\tau)$

$\triangleright$ **Algorithm 6** $\mathsf{rewrite}(a, b)$

51: $c := \min\{a, b\}$ $d := \max\{a, b\}$
52: $\gamma.\mathsf{mergeInto}(d, c)$
53: **for each** $F \in P \setminus \hat{P}$ with $d \in \mathsf{voc}(F)$ **do**
54:     $\hat{P}.\mathsf{add}(F)$ and $P.\mathsf{add}(\gamma(F))$
55: **for each** $r \in \Gamma$ with $r \neq \gamma(r)$ **do**
56:     replace r in Γ with $r' := \gamma(r)$
57:     **for each** $\tau \in [V \setminus \hat{P}].\mathsf{eval}(\mathsf{b}(r'), \emptyset, \emptyset)$ **do**
58:         $\mathsf{prove}(\mathsf{h}(r')\tau)$

$\triangleright$ **Algorithm 7** $\mathsf{prove}(F)$

59: **if** $\pi(F) \in C$ **then** $P.\mathsf{add}(F)$ **else** $Y.\mathsf{add}(F)$

Theorem 1. *Let (π, I) be the r-materialisation of a dataset E w.r.t. a program Π, and let E^- be a dataset.*

1. *Algorithm 1 terminates, at which point (π, I) contains the r-materialisation of $E \setminus E^-$ w.r.t. Π.*
2. *Each combination of a rule r and a substitution τ is considered at most once in line 50 or line 58, but not both.*
3. *Each combination of a rule r and a substitution τ is considered at most once in line 15.*

UOBM-100-L $|E| = 24.5\text{M}$ $|I^{\approx}| = 46.4\text{M}$ $T^{\approx} = 69$ $D^{\approx} = 79.3\text{M}$; $|\Pi| = 210$ $|I^{A}| = 46.7\text{M}$ $T^{A} = 122$ $D^{A} = 361\text{M}$

$\lvert E^-\rvert$	$\Delta\lvert I^{\approx}\rvert$	B/F$^{\approx}$		Remat$^{\approx}$		$\Delta\lvert I^{A}\rvert$	B/F^{A}		Remat^{A}	
		T	D	T	D		T	D	T	D
100	146	0.6	0.7k	45.1	79.3M	146	4.6	32.8k	94.6	361M
5k	7.8k	1.2	45.8k	42.5	79.3M	7.9k	7.1	805k	93.1	361M
1.3M	1.9M	18.2	8.7M	39.2	75.4M	2.0M	38.0	98.0M	89.5	361M
2.5M	3.9M	29.9	15.8M	41.7	71.5M	4.0M	54.5	151M	83.7	345M
3.8M	5.8M	31.8	22.3M	37.4	67.7M	5.9M	70.9	188M	79.3	329M
5M	7.7M	41.2	28.4M	36.2	63.8M	7.9M	73.8	218M	73.2	314M

UOBM-100-U $|E| = 24.5\text{M}$ $|I^{\approx}| = 000$ $T^{\approx} = 000$ $D^{\approx} = 000$; $|\Pi| = 279$ $|I^{A}| = 000$ $T^{A} = 000$ $D^{A} = 000$

$\lvert E^-\rvert$	$\Delta\lvert I^{\approx}\rvert$	B/F$^{\approx}$		Remat$^{\approx}$		$\Delta\lvert I^{A}\rvert$	B/F^{A}		Remat^{A}	
		T	D	T	D		T	D	T	D
100	???	???	???	???	???	???	???	???	???	???
1k	???	???	???	???	???	???	???	???	???	???
2.5k	???	???	???	???	???	???	???	???	???	???
5k	???	???	???	???	???	???	???	???	???	???

Claros-L $|E| = 18.8\text{M}$ $|I^{\approx}| = 79.5\text{M}$ $T^{\approx} = 83$ $D^{\approx} = 129\text{M}$; $|\Pi| = 1.3\text{k}$ $|I^{A}| = 102\text{M}$ $T^{A} = 3.9\text{k}$ $D^{A} = 11.0\text{G}$

$\lvert E^-\rvert$	$\Delta\lvert I^{\approx}\rvert$	B/F$^{\approx}$		Remat$^{\approx}$		$\Delta\lvert I^{A}\rvert$	B/F^{A}		Remat^{A}	
		T	D	T	D		T	D	T	D
100	209	8.3	797k	77.4	135M	819	2476	15.8G	3174	11.0G
5k	11.2k	9.1	895k	77.0	135M	18.6k	2609	15.8G	3166	11.0G
750k	1.7M	29.5	14.5M	80.9	131M	4.0M	2816	17.1G	2690	9.5G
1.5M	3.5M	46.1	26.5M	81.5	127M	10.1M	2757	17.4G	1933	7.3G
2.3M	5.3M	63.9	38.4M	77.7	123M	15.3M	3092	18.3G	1389	5.5G
3M	7.2M	78.4	48.8M	72.4	119M	19.4M	3170	18.6G	1075	4.4G

Claros-LE $|E| = 18.8\text{M}$ $|I^{\approx}| = 000$ $T^{\approx} = 000$ $D^{\approx} = 000$; $|\Pi| = 1.3\text{k}$ $|I^{A}| = 000$ $T^{A} = 000$ $D^{A} = 000$

$\lvert E^-\rvert$	$\Delta\lvert I^{\approx}\rvert$	B/F$^{\approx}$		Remat$^{\approx}$		$\Delta\lvert I^{A}\rvert$	B/F^{A}		Remat^{A}	
		T	D	T	D		T	D	T	D
100	522	16.1	617k	4397	12.6G	1132	5703	25.8G	8693	26.3G
2.5k	179k	31.6	9.9M	4430	12.6G	—	—	—	—	—
5k	427k	39.4	10.7M	4392	12.6G	435k	5845	+25.8G	9383	+26.3G
7.5k	609k	44.8	11.6M	4713	12.6G	—	—	—	—	—
10k	781k	4300	???	4627	12.6G	—	—	—	—	—

DBpedia-L $|E| = 113\text{M}$ $|I^{\approx}| = 136\text{M}$ $T^{\approx} = 49.3$ $D^{\approx} = 36.6\text{M}$; $|\Pi| = 3.4\text{k}$ $|I^{A}| = 139\text{M}$ $T^{A} = 641$ $D^{A} = 895\text{M}$

$\lvert E^-\rvert$	$\Delta\lvert I^{\approx}\rvert$	B/F$^{\approx}$		Remat$^{\approx}$		$\Delta\lvert I^{A}\rvert$	B/F^{A}		Remat^{A}	
		T	D	T	D		T	D	T	D
100	105	0.3	91	47.5	36.6M	105	8.9	1.7M	251	895M
5k	5.0k	0.4	24.4k	64.6	36.6M	5.3k	20.3	5.7M	256	895M
1.8M	1.8M	29.4	2.1M	48.7	36.3M	2.0M	50.0	72.2M	239	895M
3.5M	3.6M	38.9	3.6M	49.0	35.9M	3.9M	85.5	116M	237	881M
5.3M	5.3M	52.2	4.9M	54.3	35.5M	5.9M	89.8	152M	232	866M
7M	7.1M	63.1	6.2M	50.7	35.1M	7.8M	103	184M	227	852M

UniProt-L $|E| = 123\text{M}$ $|I^{\approx}| = 179\text{M}$ $T^{\approx} = 118$ $D^{\approx} = 183\text{M}$; $|\Pi| = 451$ $|I^{A}| = 229\text{M}$ $T^{A} = 527$ $D^{A} = 1.6\text{G}$

$\lvert E^-\rvert$	$\Delta\lvert I^{\approx}\rvert$	B/F$^{\approx}$		Remat$^{\approx}$		$\Delta\lvert I^{A}\rvert$	B/F^{A}		Remat^{A}	
		T	D	T	D		T	D	T	D
100	125	2.5	892	235	238M	125	14.3	6.0k	490	1.6G
5k	6.1k	3.4	35k	221	238M	6.1k	17.5	271k	482	1.6G
4.5M	5.7M	84.0	24.8M	204	232M	5.7M	125	190M	475	1.5G
9M	11.5M	137	46.7M	216	225M	11.5M	192	344M	478	1.5M
13.5M	17.4M	209	67.1M	220	218M	17.4M	315	483M	473	1.4G
18M	23.4M	220	86.5M	217	210M	23.4M	371	613M	481	1.4G

OpenCyc-L $|E| = 2.4\text{M}$ $|I^{\approx}| = 141\text{M}$ $T^{\approx} = 164$ $D^{\approx} = 280\text{M}$; $|\Pi| = 261\text{k}$ $|I^{A}| = 1.2\text{G}$ $T^{A} = 3.5\text{k}$ $D^{A} = 12.9\text{G}$

$\lvert E^-\rvert$	$\Delta\lvert I^{\approx}\rvert$	B/F$^{\approx}$		Remat$^{\approx}$		$\Delta\lvert I^{A}\rvert$	B/F^{A}		Remat^{A}	
		T	D	T	D		T	D	T	D
100	5.4k	15.5	405k	220	280M	50.0k	472	8.5M	3296	12.9G
1k	53.1k	1062	69.5M	222	280M	5.1M	5537	2.0G	3479	12.9G
2.5k	130k	1078	69.8M	178	279M	5.8M	5339	2.1G	3621	12.8G
5k	261k	1123	70.4M	177	279M	7.2M	5475	2.1G	3334	12.8G

Table 1: Experimental results

equalities are derived), B/F$^{\approx}$ outperforms B/F^{A}. This seems to be mainly because B/F^{A} ascribes no special meaning to $\Pi_{\approx}$ and so it does not use the optimisation from lines 37–39; thus, when trying to prove $c \approx c$, B/F^{A} performs backward chaining via rules ($\approx_4$), thus potentially examining each fact containing c. On Claros-L, although $|I^{A}|$ and $|I^{\approx}|$ are of similar sizes, I^{A} contains one constant c with $|c^{\pi}| = 306$, which gives rise to 306^3 derivations; this explains the difference in the performance of B/F$^{\approx}$ and B/F^{A}.

Remat$^{\approx}$ outperforms B/F$^{\approx}$ in cases similar to those described by Motik *et al.* (2015b). For example, UOBM contains a symmetric and transitive relation $\mathsf{hasSameHomeTownWith}$, which creates cliques of constants; B/F recomputes each changed clique, thus repeating most of the 'hard' work. Equality connects constants in cliques, which poses similar problems for B/F$^{\approx}$. For example, due to the upper bound transformation, the r-materialisation of UOBM-100-U contains a constant c such that $|c^{\pi}| = 3930$; thus, deleting 5k facts results in 961k (about 1.2% of $|I^{\approx}|$) facts being added to C, but these facts contribute to 73% of the derivations from the initial materialisation, and so B/F$^{\approx}$ repeats most of the work.

On OpenCyc-L, Remat$^{\approx}$ already outperforms B/F$^{\approx}$ on updates of 1k triples, which was surprising since the former makes more derivations than the latter. Our investigation revealed that OpenCyc-L contains about 200 rules of the form $\langle x, \mathsf{type}, y\rangle \leftarrow \langle x, R_i, y\rangle$ that never fire during forward chaining; however, to check provability of each fact of the form $\langle a, \mathsf{type}, C\rangle$, Algorithm 4 considers each of the 200 rules in line 32 in vain. After removing all such 'idle' rules manually, B/F$^{\approx}$ and Remat$^{\approx}$ could update 1k tuples in roughly the same time. Further analysis revealed that the slowdown in B/F$^{\approx}$ occurs mainly in line 40: the condition is checked for 13.3M facts F, and these give rise to 139M facts in F^{π}, each requiring an index lookup; the latter number is similar to the number of derivations in rematerialisation, which explains the slowdown. We believe that checking this condition can be made less expensive via additional book-keeping.

5 Conclusion

This paper describes what we believe to be the first approach to incremental maintenance of datalog materialisation when the latter is computed using rewriting—a common optimisation used when programs contain equality. Our algorithm proved to be to be very effective, particularly on small updates. In future, we plan to develop further optimisations that address the issues we highlighted in Section 4.

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A Proof of Theorem 1

Let Π be a program (that ascribes no special meaning to $\approx$), and let E be a dataset. A *derivation tree* for a fact F from E w.r.t. Π is a finite tree T in which each node t is labelled with a fact F_t, and each nonleaf node t is labelled with a rule $\mathsf{r}_t \in \Pi$ and a substitution σ_t such that the following holds:

D1. $\mathsf{F}_\epsilon = F$ holds for the root ϵ of T;

D2. $\mathsf{F}_t \in E$ holds for each leaf node t of T; and

D3. $\mathsf{h}(\mathsf{r}_t)\sigma_t = \mathsf{F}_t$ and $\mathsf{b}(\mathsf{r}_t)\sigma_t = \{\mathsf{F}_{t_1}, \ldots, \mathsf{F}_{t_n}\}$ hold for each nonleaf node t of T with children $t_1, \ldots, t_n$.

The *materialisation* $\Pi^\infty(E)$ of E w.r.t. Π is the smallest set containing each fact that has a derivation tree from E w.r.t. Π; this definition of $\Pi^\infty(E)$ is equivalent to the one in Section 2. The *height* of a derivation tree is the length of its longest branch; moreover, the *height* of a fact $F \in \Pi^\infty(E)$ w.r.t. E and Π is the minimum height of a derivation tree for F from E w.r.t. Π.

In the rest of this paper, we make the following assumption $(*)$: no derivation tree contains a node t where r_t is $(\approx_1)$ and $\sigma_t(x_1) = \sigma_t(x_1')$, or r_t is $(\approx_2)$ and $\sigma_t(x_2) = \sigma_t(x_2')$, or r_t is $(\approx_3)$ and $\sigma_t(x_3) = \sigma_t(x_3')$. This is w.l.o.g. because, for each such t, we have $\mathsf{F}_t = \mathsf{F}_{t_1}$ for t_1 the first child of t; hence, we can always remove such t from the derivation tree.

Next, we recapitulate Theorem 1 and present its proof, which we split into several claims.

Theorem 1. *Let (π, I) be the r-materialisation of a dataset E w.r.t. a program Π, and let E^- be a dataset.*

1. *Algorithm 1 terminates, at which point (π, I) contains the r-materialisation of $E \setminus E^-$ w.r.t. Π.*
2. *Each combination of a rule r and a substitution τ is considered at most once in line 50 or line 58, but not both.*
3. *Each combination of a rule r and a substitution τ is considered at most once in line 15.*

In the rest of this section, we fix a datalog program Π and datasets E and E^-. Let (π, I) be the r-materialisation of E w.r.t. Π; let $J := (\Pi \cup \Pi_\approx)^\infty(E)$; let $E' := E \setminus E^-$; let (π', I') be the r-materialisation of E' w.r.t. Π; and let $J' := (\Pi \cup \Pi_\approx)^\infty(E')$. By the monotonicity of datalog, we clearly have $J' \subseteq J$.

We next show that Algorithm 5 essentially captures the r-materialisation algorithm by Motik *et al.* (2015a).

Claim 1. *Let P and $\hat{P}$ be as obtained after a call to Algorithm 5 in line 23, let $K := \{d \approx d \mid d \in \mathsf{voc}(E)\}$, and let L be the set containing precisely each fact F that has a derivation T from $K \cup E'$ w.r.t. $\Pi \cup \Pi_\approx$ in which $\mathsf{F}_t \in C^\pi$ holds for each node t of T. Then, the following properties hold:*

1. *$\gamma(c) = \min \mathsf{E}_c(L)$ for each constant c;*
2. *$P \setminus \hat{P} = \gamma(L)$; and*
3. *each combination of a rule r and a substitution τ is considered at most once in line 50 or line 58, but not both.*

Proof (Sketch). Algorithm 5 is a variant of the r-materialisation algorithm by Motik *et al.* (2015a), so properties 1–3 hold by a straightforward modification of the correctness proof of that algorithm. This proof is quite lengthy so, for the sake of brevity, we just summarise the differences.

- Lines 37–39 ensure $\gamma(C^\pi \cap K) \subseteq P \setminus \hat{P}$, and line 40 ensures $\gamma(C^\pi \cap E') \subseteq P \setminus \hat{P}$; hence, $C^\pi \cap (K \cup E')$ plays the same role that explicit facts play in the algorithm by Motik *et al.* (2015a).
- Let F be an arbitrary fact considered in line 41. To ensure property 4 of Claim 1, the algorithm by Motik *et al.* (2015a) uses slightly different annotated queries to apply the rules in lines 48–49 only to facts extracted before F. In contrast, Algorithm 7 keeps track of previously processed facts in set V, but this has exactly the same effect.
- All derivations of a fact in line 47, 50, or 58, are handled by Algorithm 7, which, for each F, checks whether $\pi(F) \in C$; this is equivalent to checking $F \in C^\pi$. If the latter holds, then F is added to P, and otherwise F is added to Y. If in a subsequent invocation of Algorithm 5 set C is extended such that $\pi(F) \in C$ suddenly holds, then $\gamma(F)$ is added to P in line 40. This, however, does not change the algorithm in any substantial way. □

The following claim follows immediately from the definitions in Algorithm 3.

Claim 2. *The following properties hold for an arbitrary fact F normal w.r.t. π:*

1. $\mathsf{allProved}(F) = \mathsf{t}$ *if and only if $F \notin S$ and $F^\pi \subseteq (P \setminus \hat{P})^\gamma$; and*
2. $\mathsf{allDisproved}(F) = \mathsf{t}$ *if and only if $F^\pi \cap (P \setminus \hat{P})^\gamma = \emptyset$.*

We next show that sets C, P, $\hat{P}$, S, and γ always satisfy an important property.

Claim 3. *Assume that Algorithm 4 is applied to some fact F, mapping γ, and sets S, C, P, and $\hat{P}$ where S is normal w.r.t. π and $S^\pi \cap J' = \emptyset$, and assume that all of these satisfy the following property:*

> *($\Diamond$) for each $G \in C$, either $G^\pi \subseteq (P \setminus \hat{P})^\gamma$ or, for each fact $H \in G^\pi$, each derivation tree T for H from E' w.r.t. $\Pi \cup \Pi_\approx$, and each child t_i of the root of T, we have $\pi(F_{t_i}) \in C$.*

Then, property ($\Diamond$) remains preserved after the invocation of Algorithm 4.

Proof. The proof is by induction on recursion depth of Algorithm 4 at which a fact is added to C. For the induction base, ($\Diamond$) remains preserved if the algorithm returns in line 22.

For the induction step, assume that ($\Diamond$) holds for each fact $G \in C$ different from F after a recursive call in line 27, 30, or 34. If the algorithm returns in line 24, 28, 31, or 35, then property 1 of Claim 2 implies $F^\pi \subseteq (P \setminus \hat{P})^\gamma$, so property ($\Diamond$) remains preserved. Otherwise, consider an arbitrary fact $H \in F^\pi$ and an arbitrary derivation tree T for H from E' w.r.t. $\Pi \cup \Pi_\approx$. Let $t_1, \dots, t_n$ be the children (if any exist) of the root ϵ of T; since J contains each fact labelling a node of T, we have $\{\mathsf{F}_{t_i}, \dots, \mathsf{F}_{t_i}\} \subseteq J' \subseteq J$. Now let $F_i = \pi(\mathsf{F}_{t_i})$; by the definition of r-materialisation, we have $\{F_1, \dots, F_n\} \subseteq I$. Moreover, for each $1 \leq i \leq n$, we have $F_i \in J'$ and $S^\pi \cap J' = \emptyset$, which imply $F_i \notin S^\pi$; moreover, S is normal w.r.t. π, so $F_i \notin S$ as well. Finally, we clearly have $\pi(\mathsf{r}_\epsilon \sigma_\epsilon) = \pi(\mathsf{r}_\epsilon)\pi(\sigma_\epsilon)$, and so $\mathsf{h}(\pi(\mathsf{r}_\epsilon))\pi(\sigma_\epsilon) = F$ and $\mathsf{b}(\pi(\mathsf{r}_\epsilon))\pi(\sigma_\epsilon) = \{F_1, \dots, F_n\} \subseteq I \setminus S$. We next consider the forms of r_ϵ.

- Assume r_ϵ is of the form ($\approx_4$), so $n = 1$. Fact F_1 is eventually considered in line 26, so, due to the recursive call in line 27, we have $F_1 \in C$, as required.
- Assume r_ϵ is of the form ($\approx_1$)–($\approx_3$); thus, $n = 2$, $F_1 = F$, and $F_2 = c \approx c$ for some constant c. Fact $F_1 = F$ is added to C in line 22. Moreover, by assumption ($*$) on the shape of T, we have $F_2 = s \approx t$ with $s \neq t$; since $\pi(s) = \pi(t) = c$, we have $|c^\pi| > 1$. Thus, due to the recursive call in line 30, we have $F_2 \in C$, as required.
- Assume $\mathsf{r}_\epsilon \in \Pi$. Then, $\pi(\mathsf{r}_\epsilon) \in \pi(\Pi)$, so $\pi(\mathsf{r}_\epsilon)$ and $\pi(\sigma_\epsilon)$ are eventually considered in lines 32 and 33; hence, due to the recursive call in line 34, we have $F_i \in C$ for each $1 \leq i \leq n$, as required. $\square$

Calls in line 6 ensure another property on C, P, $\hat{P}$, and S.

Claim 4. *The following properties hold after each line of Algorithm 1:*

1. *property ($\Diamond$) is satisfied;*
2. $(P \setminus \hat{P})^\gamma = C^\pi \cap J'$*;*
3. $\gamma(c) = \min \mathsf{E}_c(C^\pi \cap J')$ *for each constant c; and*
4. $S^\pi \cap J' = \emptyset$*.*
5. *For each fact $F \in O$, we have $F^\pi \not\subseteq J'$.*
6. $D \subseteq C$*.*

Proof. The proof is by induction on the number of iterations of the loop in lines 5–16. For the induction base, we have $S = C = P = O = \emptyset$ in line 1, so properties 1–5 clearly hold initially. For the induction step, assume that all properties hold before line 6. Due to property 4 and Claim 3, property 1 remains preserved after line 6; hence, we next consider properties 2–6.

(Property 2) Let K and L be as stated in Claim 1; note that property 2 of Claim 1 is equivalent to $(P \setminus \hat{P})^\gamma = L$. We first show $(P \setminus \hat{P})^\gamma \subseteq C^\pi \cap J'$. Since $K \subseteq J'$, we clearly have $J' = (\Pi \cup \Pi_\approx)^\infty(K \cup E')$. Moreover, for each $F \in (P \setminus \hat{P})^\gamma$ we have $F \in L$, so by the definition of L there exists a derivation tree T for F from $K \cup E'$ w.r.t. $P \cup \Pi_\approx$ such that $\mathsf{F}_t \in C^\pi$ holds for each node t of T; but then, we clearly have $F \in C^\pi \cap J'$. We next prove $C^\pi \cap J' \subseteq (P \setminus \hat{P})^\gamma$ by induction on the height h of a fact $F \in C^\pi \cap J'$ w.r.t. E' and $\Pi \cup \Pi_\approx$.

- If $h = 0$, then $F \in E'$; since $F \in C^\pi$, by the definition of L we have $F \in L$; but then, $F \in (P \setminus \hat{P})^\gamma$ as well.
- Assume that the claim holds for each fact in $C^\pi \cap J'$ whose height w.r.t. E' and $\Pi \cup \Pi_\approx$ is at most h, and consider an arbitrary fact $F \in C^\pi \cap J'$ with height $h + 1$; let T be the corresponding derivation tree for F. Moreover, assume that $F \notin (P \setminus \hat{P})^\gamma$; then, $F \in C^\pi$ implies $\pi(F) \in C$; hence, property ($\Diamond$) ensures that, for each child t_i of the root of T, we have $\pi(\mathsf{F}_{t_i}) \in C$, which is equivalent to $\mathsf{F}_{t_i} \in C^\pi$. Now the height of each F_{t_i} w.r.t. E' and $\Pi \cup \Pi_\approx$ is at most h so, by the induction assumption, we have $\mathsf{F}_{t_i} \in (P \setminus \hat{P})^\gamma = L$. The latter ensures that, for each F_{t_i}, there exists a derivation tree T_i in which each node is labelled by a fact contained in C^π. Let T' be the derivation tree in which the root ϵ is labelled with the same fact, rule, and substitution as in T, and each T_i is a subtree of ϵ. Clearly, T' is a derivation tree for F from E' w.r.t. $\Pi \cup \Pi_\approx$ in which each node is labelled by a fact contained in C^π; thus, by the definition of L, we have $F \in L = (P \setminus \hat{P})^\gamma$, as required.

(Property 3) This property follows directly from property 1 of Claim 1 and property 2 of Claim 4.

(Property 4) Assume that some fact G is added to S in line 7. Then $\mathsf{allDisproved}(G) = \mathsf{t}$, which by property 2 of Claim 2 implies $G^\pi \cap (P \setminus \hat{P})^\gamma = \emptyset$. Property 2 of Claim 4 holds at this point, so we have $G^\pi \cap C^\pi \cap J' = \emptyset$. Finally, lines 6 and 22 ensure $G \in C$, so we have $G^\pi \subseteq C^\pi$; thus, $G^\pi \cap J' = \emptyset$, and so adding G to S preserves property 4.

(Property 5) Assume that some fact F is added to O in line 16. Then $\mathsf{allProved}(F) = \mathsf{f}$, which by property 1 of Claim 2 implies $F \in S$ or $F^\pi \not\subseteq (P \setminus \hat{P})^\gamma$. In the former case, $F^\pi \not\subseteq J'$ holds directly from property 4. In the latter case, property 2 of

Claim 4 holds at this point, so we have $F^\pi \not\subseteq C^\pi \cap J'$; moreover, lines 6 and 22 ensure $F \in C$, which implies $F^\pi \subseteq C^\pi$; this, in turn, implies $F^\pi \not\subseteq J'$. Consequently, adding F to O preserves property 5.

(Property 6) Each fact F extracted from D in line 5 is passed in line 6 to Algorithm 4, which in turn ensures that F is added to C in line 22. $\square$

We next show that set D contains each fact that needs to be deleted, and each fact that contains a constant whose representative changes as a result of the update.

Claim 5. *For each fact $F \in J \setminus J'$, the following two properties hold in line 17:*

1. *$\pi(F) \in D$, and*
2. *if $F = s \approx t$ with $s \neq t$, then D contains each fact $G \in I$ such that $\pi(s) \in \mathsf{voc}(G)$ and $G^\pi \not\subseteq J'$.*

Proof. Consider an arbitrary fact $F \in J \setminus J'$.

(Property 1) We prove the claim by induction on the height h of F w.r.t. E and $\Pi \cup \Pi_\approx$; the notion of the height of F is correctly defined because $F \in J$. For the induction base, assume $h = 0$; now $F \in J$ implies $F \in E$; moreover, $F \notin J'$ implies $F \notin E'$; thus, $F \in E^-$, and so $\pi(F)$ is added to D in lines 3–4. For the induction step, assume that the claim holds for each fact in $J \setminus J'$ whose height w.r.t. E and $\Pi \cup \Pi_\approx$ is at most h, and assume that the height of F w.r.t. E and $\Pi \cup \Pi_\approx$ is $h+1$. Let T be a corresponding derivation tree for F from E w.r.t. $\Pi \cup \Pi_\approx$; let $t_1, \ldots, t_n$ be the children of the root ϵ of T; and let $F_i = \pi(\mathsf{F}_{t_i})$ for each $1 \leq i \leq n$. Moreover, let N contain precisely each F_i, $1 \leq i \leq n$, such that $F_i \in D$ and $F_i^\pi \not\subseteq J$. Since $F \notin J'$, some j with $1 \leq j \leq n$ exists such that $\mathsf{F}_{t_j} \notin J'$; moreover, T is a derivation tree for F from E w.r.t. $\Pi \cup \Pi_\approx$, so $\mathsf{F}_{t_j} \in J$ and the height of F_{t_j} is at most h; but then, we have $\pi(\mathsf{F}_{t_j}) = F_j \in D$ by the induction hypothesis, and so we also have $F_j \in N$—that is, $N \neq \emptyset$. Each fact in D is eventually considered in line 5; thus, let F' be the fact from N that is consider first. At that point, we have $O \cap N = \emptyset$ because facts are added to added to O in line 16 only after they have been considered; hence, $F_i \in I \setminus O$ holds at this point for each $1 \leq i \leq n$. Furthermore, $F' \in D \subseteq C$ implies $(F')^\pi \subseteq C^\pi$; but then, $(F')^\pi \not\subseteq J'$ and property 2 of Claim 4 imply $(F')^\pi \not\subseteq (P \setminus \hat{P})^\gamma$; thus, property 1 of Claim 2 ensures we have $\mathsf{allProved}(F') = \mathsf{f}$ and so the check in line 8 passes. We next consider the possible forms of the rule r_ϵ.

- Assume that r_ϵ is $(\approx_1)$–$(\approx_3)$. Then, we clearly have $\pi(F) = F_1$; fact F_{t_2} is of the form $\mathsf{F}_{t_2} = s \approx t$ with $s \neq t$ and $c = \pi(s) = \pi(t)$; and $c \in \mathsf{voc}(F_1)$. We have two possible ways to choose F'. If $F' = F_1$, then $\pi(F) = F_1 = F' \in D$ holds. If $F' = F_2$, then $s \neq t$ by assumption $(*)$ on the shape of T, so $|c^\pi| > 1$ and the check in line 9 passes; furthermore, due to $F_1 \in I \setminus O$, we eventually consider fact $G = F_1 = \pi(F)$ in line 10 and add it to D in line 11.
- Assume that r_ϵ is $(\approx_4)$. Then, F is of the form $s \approx s$ so $\pi(F) = c \approx c$ for $c = \pi(s)$; clearly, we have $c \in \mathsf{voc}(F')$ and $F' = F_1$. But then, $\pi(F)$ is added to D in line 12.
- Assume that $\mathsf{r}_\epsilon \in \Pi$. We clearly have $\pi(\mathsf{r}_\epsilon\sigma_\epsilon) = \pi(\mathsf{r}_\epsilon)\pi(\sigma_\epsilon)$; therefore, we have $\pi(F) = \pi(\mathsf{h}(\mathsf{r}_\epsilon\sigma_\epsilon)) = \mathsf{h}(\pi(\mathsf{r}_\epsilon))\pi(\sigma_\epsilon)$ and $\pi(\mathsf{b}(\mathsf{r}_\epsilon\sigma_\epsilon)) = \{F_1, \ldots, F_n\} = \mathsf{b}(\pi(\mathsf{r}_\epsilon))\pi(\sigma_\epsilon) \subseteq I \setminus O$. Moreover, we clearly have $\pi(\mathsf{r}_\epsilon) \in \pi(\Pi)$. Finally, let i be the smallest integer with $1 \leq i \leq n$ such that $F_i = F'$, and let Q be annotated query (2) obtained from $\pi(\mathsf{r}_\epsilon)$ for that i; clearly, the way in which we chose i ensures $F_j \neq F'$ for each j with $1 \leq j < i$. All of these observations ensure together that $\langle \pi(\mathsf{r}_\epsilon), Q, \sigma) \rangle \in \pi(\Pi).\mathsf{matchBody}(F')$ is considered in line 13, and that $\pi(\sigma_\epsilon)$ is considered in line 14; consequently, $\pi(F)$ is added to D in line 15.

(Property 2) Assume that F is of the form $F = s \approx t$ with $s \neq t$, let $c = \pi(s) = \pi(t)$, and let $F' = \pi(F)$. Property 1 of this claim ensures $F' = c \approx c \in D \subseteq C$, and so we have $(F')^\pi \subseteq C^\pi$; but then, together with $F \notin J'$, property 2 of Claim 4 ensures $(F')^\pi \not\subseteq (P \setminus \hat{P})^\gamma$; finally, property 1 of Claim 2 ensures $\mathsf{allProved}(F') = \mathsf{f}$. Fact F' is eventually processed in line 5, and by the previous discussion the check in line 8 passes. Moreover, $s \neq t$ implies $|c^\pi| > 1$, so the check in line 9 passes as well. Now consider an arbitrary fact $G \in I$ such that $c \in \mathsf{voc}(G)$ and $G^\pi \not\subseteq J'$; property 5 of Claim 4 ensures $G \notin O$, and therefore G is added to D in line 11. $\square$

We next show that Algorithm 1 correctly updates I to I'.

Claim 6. *Algorithm 1 updates set I to I'.*

Proof. Property 6 of Claim 4 and property 1 of Claim 5 clearly ensure that (3) holds. Furthermore, property 2 of Claim 4 clearly ensures that (4) holds.

$$J \setminus J' \subseteq D^\pi \subseteq C^\pi \tag{3}$$

$$(P \setminus \hat{P})^\gamma \subseteq J' \subseteq J \tag{4}$$

For convenience we recapitulate the definitions of $\pi(c)$, $\pi'(c)$, and $\gamma(c)$; note that (7) follows immediately from properties 2 and 3 of Claim 4. Finally, (4), (6), and (7) clearly imply (8).

$$\pi(c) = \min \mathsf{E}_c(J) \tag{5}$$

$$\pi'(c) = \min \mathsf{E}_c(J') \tag{6}$$
$$\gamma(c) = \min \mathsf{E}_c((P \setminus \hat{P})^\gamma) \tag{7}$$
$$\pi'((P \setminus \hat{P})^\gamma) = \pi'(P \setminus \hat{P}) \tag{8}$$

Before proceeding, we prove several useful properties. Consider an arbitrary constant c with $\pi(c) = c$; by (4) and (5)–(7), we clearly have $\pi'(c) = c$ and $\gamma(c) = c$. Thus, for each fact F with $\pi(F) = F$, we have $\pi'(F) = F$ and $\gamma(F) = F$, which ensures the following properties:

$$\begin{array}{lll} F \in I \text{ iff } F \in J, & F \in I' \text{ iff } F \in J', & F \in (P \setminus \hat{P})^\gamma \text{ iff } F \in P \setminus \hat{P}, \\ F \in D \text{ iff } F \in D^\pi, \text{ and} & F \in C \text{ iff } F \in C^\pi. & \end{array} \tag{9}$$

We next show that lines 18–19 update π to π'. To this end, consider arbitrary constants c and d with $\pi(d) = c$, and let $F = c \approx c$. Set F^π clearly contains each triple of the form $d \approx e \in J$, which, together with (4), implies

$$\mathsf{E}_d(F^\pi \cap (P \setminus \hat{P})^\gamma) = \mathsf{E}_d((P \setminus \hat{P})^\gamma), \qquad \mathsf{E}_d(F^\pi \cap J') = \mathsf{E}_d(J'), \qquad \text{and} \qquad \mathsf{E}_d(F^\pi \cap J) = \mathsf{E}_d(J). \tag{10}$$

We now consider two possible cases.

- Assume that $F \in C$. Thus, $F^\pi \subseteq C^\pi$ holds, so property 2 of Claim 4 ensures $F^\pi \cap (P \setminus \hat{P})^\gamma = F^\pi \cap J' = V$. But then, (10) imply $\mathsf{E}_d(V) = \mathsf{E}_d(J') = \mathsf{E}_d((P \setminus \hat{P})^\gamma)$. Finally, (6) and (7) imply $\pi'(d) = \gamma(d)$.
- Assume that $F \notin C$. We thus have $F^\pi \cap C^\pi = \emptyset$; but then, $J \setminus J' \subseteq C^\pi$ implies $F^\pi \cap (J \setminus J') = \emptyset$, which then implies $F^\pi \cap J = F^\pi \cap J'$. Finally, (5), (6), and (10) together imply $\pi'(d) = \pi(d)$.

We next prove $I \setminus I' = D \setminus (P \setminus \hat{P})$ and hence show that line 20 correctly deletes the relevant facts. To this end, we next consider each side of the inclusion.

- Assume that $F \in I \setminus I'$. Then $F \in I$ implies $\pi(F) = F$, so by (9) we have $F \in J \setminus J'$. By (3) we have $F \in D^\pi \subseteq C^\pi$, and by (9) we have $F \in D \subseteq C$. Moreover, $F \notin J'$ and property 2 of Claim 4 imply $F \notin (P \setminus \hat{P})^\gamma$, which by (9) implies $F \notin P \setminus \hat{P}$. Consequently, we have $F \in D \setminus (P \setminus \hat{P})$.
- Assume that $F \in D \setminus (P \setminus \hat{P})$. Then $D \subseteq I$ implies $F \in I$, so $\pi(F) = F$. Also, $F \notin P \setminus \hat{P}$ and (9) imply $F \notin (P \setminus \hat{P})^\gamma$. But then, property 2 of Claim 4 ensures $F \notin C^\pi \cap J'$. Due to $D \subseteq C$ and (9), we have $F \in C^\pi$; thus, $F \notin J'$, so by (9) we have $F \notin I'$. Consequently, we have $F \in I \setminus I'$.

We finally prove that $I' = [I \setminus (I \setminus I')] \cup \pi'(P \setminus \hat{P})$ and hence show that line 21 correctly adds the relevant facts; please remember that, due to updates in lines 18–19, mapping π actually contains π' in line 21.

- Assume that $F \in [I \setminus (I \setminus I')] \cup \pi'(P \setminus \hat{P})$. We consider two cases.
  - Assume that $F \in I \setminus (I \setminus I')$. Thus, $F \in I$ and $F \notin I \setminus I'$; but then, we have $F \in I'$, as required.
  - Assume that $F \in \pi'(P \setminus \hat{P})$. Then, some $G \in (P \setminus \hat{P})^\gamma$ exists such that $\pi'(G) = F$. By property 2 of Claim 4, we have $G \in J'$; but then, we have $\pi'(G) = F \in I'$, as required.
- Assume that $F \in I'$ and $F \notin I \setminus (I \setminus I')$. Thus, $F \notin I$, but clearly $F \in J' \subseteq J$. Due to the latter, some $G \in I$ exists such that $\pi(F) = G$; clearly, $F \neq G$ and $G^\pi \nsubseteq J$. Since $G \in I$, we have $\pi(G) = G$; thus, by (9) we have $\pi'(G) = G$. Moreover, $F \in I'$ implies $\pi'(F) = F$. Consequently, distinct constants $a \in \mathsf{voc}(F)$ and $b \in \mathsf{voc}(G)$ exist such that $a \approx b \in J \setminus J'$; but then, property 2 of Claim 5 and $G^\pi \nsubseteq J$ ensure that $G \in D \subseteq C \subseteq C^\pi$, which ensures $F \in C^\pi$. Since $F \in J'$, by property 2 of Claim 4 we have $F \in (P \setminus \hat{P})^\gamma$; but then, by (8) we have $F \in \pi'(P \setminus \hat{P})$, as required. □

We next show that Algorithm 1 does not repeat derivations.

Claim 7. *Each combination of a rule r and a substitution τ is considered at most once in line 15.*

Proof. Assume that a rule $r \in \Pi$ and substitution τ exist that are considered in line 15 twice, when (not necessarily distinct) facts F and F' are extracted from D. Moreover, let B_i and $B_{i'}$ be the body atoms of r that τ matches to F and F'—that is, $F = B_i\tau$ and $F' = B_{i'}\tau$. Finally, let Q' be the annotated query considered in line 13 when atom $B_{i'}$ of r is matched to F'. We have the following possibilities.

- Assume that $F = F'$. Then, B_i and $B_{i'}$ must be distinct, so w.l.o.g. assume that $i \leq i'$. But then, query Q' contains atom $B_i^{\neq}$, so τ cannot be returned in line 14 when evaluating Q'.
- Assume that $F \neq F'$ and that, w.l.o.g. F is extracted from D before F'. Then, we have $F \in O$ due to line 16, and therefore we have $F \notin I \setminus O$; consequently, τ cannot be returned in line 14 when evaluating Q'. □