Query Based Access Control for Linked Data

Sabrina Kirrane\textsuperscript{1}, Alessandra Mileo\textsuperscript{2}, Axel Polleres\textsuperscript{1}, and Stefan Decker\textsuperscript{3}

\textsuperscript{1}Vienna University of Economics and Business, Austria
\textsuperscript{2}Dublin City University, Ireland
\textsuperscript{3}Fraunhofer FIT, RWTH Aachen University, Germany

Dated: January 1, 2016

Abstract

In recent years we have seen significant advances in the technology used to both publish and consume Linked Data. However, in order to support the next generation of ebusiness applications on top of interlinked machine readable data suitable forms of access control need to be put in place. Although a number of access control models and frameworks have been put forward, very little research has been conducted into the security implications associated with granting access to partial data or the correctness of the proposed access control mechanisms. Therefore the contributions of this paper are two fold: we propose a query rewriting algorithm which can be used to partially restrict access to SPARQL 1.1 queries and updates; and we demonstrate how a set of criteria, which was originally used to verify that an access control policy holds over different database states, can be adapted to verify the correctness of access control via query rewriting.

1 Introduction

The term Linked Data Web (LDW) is used to describe a World Wide Web where data is directly linked with other relevant data using machine-accessible formats \cite{link1, link2}. Although the LDW has seen considerable growth in recent years, the focus continues to be on linking public data. This can partially be attributed to the fact that no formal recommendation exists for allowing partial access to Linked Data based on predefined access control policies.

Several researchers have proposed access control strategies for the Resource Description Framework (RDF), which could be applied to Linked Data. Broadly speaking, these frameworks enforce access control either at the data layer \cite{link3, link4}, the query layer \cite{link5, link6, link7, link8} or a combination of both \cite{link9}. Enforcement of access control at the data layer is concerned with removing unauthorised data from a dataset. Whereas, enforcement at the query layer relies on using query rewriting techniques to ensure that only authorised query results are returned.

Given we need to cater for many users, with many different authorisations a filtering approach will not scale well, therefore in this paper we adopt a query
rewriting approach. To date researchers have proposed query rewriting strategies that involve adding contextual information pertaining to the requester to the query using path expressions and bindings \[1, 2, 11\], or adding bindings for authorised/unauthorised classes, properties or instances using filters \[2, 10\]. Our query rewriting strategy builds on the latter approach by demonstrating how quad patterns can be used to grant or deny access to RDF data at multiple levels of granularity (triple, named graph, classes, properties, instances). In addition, we demonstrate how our query rewriting strategy can be used not only to enforce access control over basic graph patterns but also in conjunction with SPARQL 1.1 queries that include subqueries and negation, graph update operations and graph management operations. Although in this paper we discuss how access can be restricted to a single quad pattern as we use \texttt{FILTER NOT EXISTS} to deny access to unauthorised data our approach can easily be extended to work with graph patterns. In order to verify the effectiveness of our query rewriting strategy, we define a set of criteria that can be used to compare the results obtained when a query is executed over a dataset where all unauthorised data has been removed, and the results obtained when a query is rewritten and executed over a dataset, which contains both authorised and unauthorised data. The contributions of the paper can be summarised as follows: we (i) formally define a set of criteria which can be used to verify the correctness of access control via query rewriting; (ii) propose query rewriting strategies that can be used to partially restrict access to SPARQL 1.1 queries and updates; and (iii) demonstrate how the proposed correctness criteria can be used to verify existing query rewriting strategies.

The remainder of the paper is structured as follows: \textit{Section 2} describes the different data filtering and query rewriting strategies that are used to restrict access to RDF data. \textit{Section 3} presents a set of correctness criteria, which allows for access control via query rewriting to be compared to access control via data filtering. \textit{Section 4} proposes query rewriting strategies for both SPARQL 1.1 queries and updates. In \textit{Section 5} we use the proposed correctness criteria to evaluate both an existing query rewriting strategy and the alternative strategy presented in this paper. Finally, we present conclusions and directions for future work in \textit{Section 6}.

2 Related Work

Both Dietzold and Auer \[4\] and Muhleisen et al. \[8\] adopt a filtering approach to access control over RDF data. Dietzold and Auer \[4\] propose access control policy specification at multiple levels of granularity (triples, classes and properties). Authorisations are used to associate filters (SPARQL \texttt{CONSTRUCT} queries) with users and resources. When a requester submits a query, a virtual model is created based on the matched authorisations. The query is subsequently executed against the virtual model, which only contains data that the requester is authorised to access. Whereas, Muhleisen et al. \[8\] allow access control policies to be specified for triple patterns, resources or instances using SWRL rules. When a requester submits a query, the system uses the access control rules to generate a temporary named graph containing only authorised data. The requesters query is subsequently executed against the temporary named graph and the results are returned to the user.
A number of researchers Abel et al. \cite{1}, Franzoni et al. \cite{5}, Oulmakhzoune et al. \cite{11} have proposed strategies that involve adding policy information to the query (for example, the requester can only see information relating to papers that they have authored). Abel et al. \cite{1} specify authorisations in terms of sets of contextual predicates, path expressions and boolean expressions that are used to restrict access to instance data. For positive authorisations, the path expressions and the bindings are appended to the query WHERE clause. For negative authorisations, the path expressions and the bindings are added to a MINUS clause, which in turn is appended to the query. Franzoni et al. \cite{5} also propose a query rewriting strategy which is used to grant/deny access to ontology instances, based on contextual information pertaining to the user or the environment. Like Abel et al. \cite{1} bindings are generated for path expressions specified in the access control policy and both the path expressions and the bindings are added to the query WHERE clause. Oulmakhzoune et al. \cite{11} extend previous work by demonstrating how the SERVICE operator can be used to return bindings based on an external privacy preferences policy.

Both Chen and Stuckenschmidt \cite{2} and Oulmakhzoune et al. \cite{10} use simple filters to bind/unbind query solutions based on access control policies that are specified for specific classes, properties or individuals. According to the rewriting strategy proposed by Oulmakhzoune et al. \cite{10}, when access is prohibited to predicates or objects, the relevant triple patterns are made OPTIONAL. Although both Chen and Stuckenschmidt \cite{2} and Oulmakhzoune et al. \cite{10} propose query rewriting strategies for SPARQL queries, the authors focus specifically on SELECT queries composed of basic graph patterns and no special consideration is given to complex SPARQL queries that include subqueries or negation.

Costabello et al. \cite{3} also use contextual data to restrict access to RDF. However, the proposed query rewriting strategy restricts access to named graphs as opposed to specific classes, properties and instances. Li and Cheung \cite{7} propose a query rewriting strategy for views generated from ontological relations. The proposed query rewriting strategy involves expanding the view concepts to include implicit concepts, retrieving both explicit and implicit access control policies and adding range and instance restrictions, associated with the matched authorisation, to the view query.

When it comes to the evaluations of the aforementioned access control strategies only Oulmakhzoune et al. \cite{11} examine the correctness of their access control strategy. The authors present a set of criteria which is used by Wang et al. \cite{12} to verify that a given access control policy holds over different relational database states and discuss how their algorithm satisfies the criteria. However, no formal evaluation is performed.

In contrast to other approaches, our query rewriting strategy can be used not only to enforce access control over basic graph patterns but also in conjunction with SPARQL 1.1 queries that include subqueries and negation, graph update operations and graph management operations. In addition, we demonstrate how a set of correctness criteria, that was originally used to verify that a given access control policy holds over different database states, can be adapted to verify the correctness of access control via query rewriting, by performing a comparison with access control via data filtering. As the formal correctness criteria we propose in this paper is not specific to RDF, it can be used in conjunction with any non-monotonic query language.
3 Access Control Correctness Criteria

According to Wang et al. [12] a query processing algorithm should be secure, sound and maximum. An algorithm is secure if it does not return information which has not been authorised. An algorithm is sound if it does not return invalid results. Furthermore, an algorithm is maximum if it returns as much information as possible without violating the secure and sound constraints. In its current form, the formal correctness criteria presented in Wang et al. [12] is unsuitable for the verification of access control over RDF data. Although it is possible to use their formalism to verify that a secure query processing algorithm holds over different database states, it cannot be used to verify that the algorithm is in fact secure, nor can it be used in conjunction with non monotonic queries such as MINUS and FILTER NOT EXISTS. Therefore, in this paper we redefine each of the criteria to cater for a comparison between the results obtained when: (i) a query is executed against a dataset which is generated by removing the unauthorised data (henceforth referred to as filtering); and (ii) when the same query is rewritten so that unauthorised data will not be returned and subsequently executed over the unmodified dataset (which we refer to as rewriting). In the definitions that follow the term dataset is used to denote a collection of RDF graphs, which can include a default graph and one or more named graphs. In this paper we assume that the dataset does not contain blank nodes. Before formally defining the correctness criteria we provide definitions for an authorised dataset and an unauthorised dataset:

Definition 1 (Authorised Dataset and Unauthorised Dataset). Let $D$ denote a dataset and $P$ an access control policy. Given $D$ and $P$, let $DG$ denote the set of quads in $D$ where access is granted by $P$ and $DD$ the set of quads in $D$ where access is denied by $P$. Assuming that $DG$ is disjoint from $DD$, then $DG$ is the RDF subgraph of $D$ which is authorised by $P$, and $DD$ is the RDF subgraph of $D$ which is unauthorised by $P$.

3.1 Correctness Criteria for Non-Monotonic Queries

When access control via query rewriting is compared to access control via data filtering, a query rewriting algorithm is deemed secure if each of the resources returned by the algorithm are present in the authorised dataset. The algorithm is sound if all of the results returned by the algorithm are also present in the result set which is generated when the original query is executed over the authorised dataset. The algorithm is maximum if the data returned by the algorithm is equivalent to the data returned when the query is executed over the authorised dataset. We formally redefine the correctness criteria proposed by Wang et al. [12] as follows:

Definition 2 (Query correctness criteria). Given our definition of an authorised dataset $DG$, let $S$ denote a query processing algorithm without access control. It follows that when query $Q$ is executed on $DG$ the result set returned by $S(DG, Q)$ only contains authorised data.

Let $A(D, P, Q)$ represent a query processing algorithm with access control, which returns the result set authorised by $P$ when query $Q$ is executed on $D$. A query
3.2 Correctness Criteria for Updates

Although Wang et al. [12] focused specifically on queries, in this paper we are also interested in updates. As SPARQL 1.1 updates change the state of the dataset, it is necessary to examine the resulting datasets as opposed to comparing the query results. Here we use the term rewritten dataset to refer to the dataset which is generated when a rewritten query is executed against a given dataset, and the term merged filtered dataset to refer to the merge of the unauthorised dataset with the authorised dataset after the update query has been executed. A delete query processing algorithm is deemed secure, if every resource that is in the merged filtered dataset, is in the rewritten dataset. The algorithm is sound, if the rewritten dataset does not contain less resources than the merged filtered dataset. The algorithm is maximum, if the rewritten dataset is equivalent to the merged filtered dataset. An insert query processing algorithm is deemed secure, if all of the data contained in the rewritten dataset is also in the merged filtered dataset. The algorithm is sound, if the rewritten dataset does not contain more resources than the merged filtered dataset. The algorithm is maximum, if all of the rewritten dataset is equivalent to the merged filtered dataset.

Definition 3 (Update correctness criteria). Given our definitions for an authorised dataset $DG$ and an unauthorised dataset $DD$, let $U$ denote an update query processing algorithm without access control. It follows that when query $Q$ is executed on $DG$ the dataset generated by $U(DG, Q)$ only contains authorised data.
Let $UD$ denote a delete processing algorithm with access control, where $UD(D, P, Q)$ produces a new dataset when query $Q$ is executed on the subset of $D$ which is authorised by policy $P$. A delete query processing algorithm is:

Secure if and only if

$$\forall P \forall Q \forall D \forall r \forall DG \forall DD \forall r [r \in (U(DG, Q) \cup DD) \implies r \in UD(D, P, Q)].$$

Sound if and only if

$$\forall P \forall Q \forall D \forall DG \forall DD [UD(D, P, Q) \subseteq (U(DG, Q) \cup DD)].$$

Maximum if and only if

$$\forall P \forall Q \forall D \forall DG \forall DD [UD(D, P, Q) \equiv (U(DG, Q) \cup DD)].$$

Let $UI$ denote an insert processing algorithm with access control and $UI(D, P, Q)$ produces a new dataset when query $Q$ is executed on the subset of $D$ which is authorised by policy $P$. An insert query processing algorithm is:

Secure if and only if

$$\forall P \forall Q \forall D \forall r \forall DG \forall DD [r \in UI(D, P, Q) \implies r \in (U(DG, Q) \cup DD)].$$

Sound if and only if

$$\forall P \forall Q \forall D \forall DG \forall DD [UI(D, P, Q) \subseteq (U(DG, Q) \cup DD)].$$

Maximum if and only if

$$\forall P \forall Q \forall D \forall DG \forall DD [UI(D, P, Q) \equiv (U(DG, Q) \cup DD)].$$

4 Query Rewriting for SPARQL Queries and Updates

An RDF triple is used to asserts a binary relationship between two pieces of information. A triple is represented as a tuple $\langle S, P, O \rangle \in (U \cup B) \times (I) \times (I \cup B \cup L)$, where $S$ is called the subject, $P$ the predicate, and $O$ the object and $I, B$ and $L$, are used to represent Internationalized Resource Identifier (IRIs), blank nodes and literals respectively. A triple pattern is a triple that can potentially contain variables in the subject, predicate and object positions. A quad pattern is a an extension of a triple pattern where the fourth element is used to denote the named graph, which can take the form of either an IRI or a variable. In this paper, we focus specifically on rewriting the query to filter out the data which has been restricted, as such we assume that an authorisation framework has already determined the unauthorised quad patterns that are relevant for a given query. Although we demonstrate how access can be restricted to a quad pattern, the approach can easily be extended to work with graph patterns. We use the foaf prefix to denote the FOAF Vocabulary [http://xmlns.com/foaf/0.1/](http://xmlns.com/foaf/0.1/) and the entx prefix to refer to our sample enterprise vocabulary [http://example.org/entrex/](http://example.org/entrex/). The query results presented throughout this paper are based on the sample data presented in Figure 1 and the authorisations presented in Figure 2. The quad pattern, entx:MRyan entx:salary ?o ?g, denies access to May Ryan’s salary. Whereas, entx:MRyan entx:worksFor ?o ?g, restricts access to information pertaining to the people that May Ryan works for.

1FOAF vocabulary Specification, [http://xmlns.com/foaf/spec/](http://xmlns.com/foaf/spec/)
4.1 SPARQL Queries

The SPARQL query language supports four distinct query types (SELECT, ASK, CONSTRUCT and DESCRIBE). In each case, SPARQL graph pattern matching is used in order to determine the output of the query. Although the queries presented in this section are limited to SELECT queries, the proposed query rewriting strategy is identical for each of the query types.

Basic Graph Patterns and Aggregate. Basic Graph Patterns (BGPs) are sets of triple patterns and aggregates are functions that are applied to groups of solutions, for example COUNT, SUM, MIN, MAX, AVG, GROUP, CONCAT and SAMPLE. When we execute Query 1 without any access restrictions the identifiers, names and the salaries of all persons are returned.

Query 1 (Basic graph pattern). Given the following query:

```sparql
SELECT ?id ?name ?salary WHERE { GRAPH entx:EmployeeDetails {
  ?id foaf:name ?name . ?id entx:salary ?salary .
} }
```

The output is as follows:

| ?id   | ?name           | ?salary |
|-------|-----------------|---------|
| entx:JBloggs | "Joe Bloggs" | 60000   |
| entx:MRyan    | "May Ryan"    | 33000   |
| entx:JSmyth   | "John Smyth"  | 33000   |

However, if the requester is denied access to the salary pertaining to entx:MRyan, by authorisation 1 in Figure 2, we need to filter out the restricted data. This can be achieved by using a FILTER NOT EXISTS to filter out unauthorised data and adding it to the relevant graph pattern group. Query 2 limits the result set to the identities, names and salaries of authorised persons.
Query 2 (Basic graph pattern restricted using binding). *Given the following query:*

```sparql
SELECT ?id ?name ?salary WHERE { GRAPH entx:EmployeeDetails {
  ?id foaf:name ?name. ?id entx:salary ?salary
  FILTER NOT EXISTS { GRAPH entx:EmployeeDetails {
    ?id foaf:name ?name. ?id entx:salary ?salary
    FILTER ( ?id = entx:MRyan ) } } } }
```

*The output is as follows:*

| ?id    | ?name          | ?salary |
|--------|----------------|---------|
| entx:JBloggs | "Joe Bloggs"  | 60000   |
| entx:JSmyth  | "John Smyth"   | 33000   |

**Subqueries and Filters.** In SPARQL 1.1, negation can be achieved by filtering query results using `FILTER EXISTS`, `FILTER NOT EXISTS` or `MINUS` expressions. Although subqueries are not classified under negation, such queries are used to limit the result set based on the results of an embedded query. The following queries are constructed using an inner `SELECT` query, however the query rewriting strategy is the same for queries that contain `FILTER EXISTS`, `FILTER NOT EXISTS` and `MINUS` expressions. *Query 3* returns the names of all people and the names of the people that they work for.

**Query 3 (Subqueries).** *Given the following query:*

```sparql
SELECT DISTINCT ?employee ?manager WHERE { GRAPH ?g {
  ?x foaf:name ?employee . ?y foaf:name ?manager
  SELECT ?x ?y WHERE { GRAPH ?g { ?x entx:worksFor ?y } } }
}
```

*The output is as follows:*

| ?employee | ?manager       |
|-----------|----------------|
| "John Smyth" | "May Ryan"  |
| "May Ryan"      | "Joe Bloggs" |

As authorisation 2 in *Figure 2* matches a quad in the inner query we add a `FILTER NOT EXISTS` to the relevant graph pattern group in the subquery. *Query 4* results in the filtering of May Ryan and her manager from the result set.

**Query 4 (Subqueries restricted with binding).** *Given the following query:*

```sparql
SELECT DISTINCT ?employee ?manager WHERE { GRAPH ?g {
  ?x foaf:name ?employee . ?y foaf:name ?manager
  SELECT ?x ?y WHERE { GRAPH ?g { ?x entx:worksFor ?y }
  FILTER NOT EXISTS { GRAPH ?g { ?x entx:worksFor ?y
  FILTER ( ?x = entx:MRyan ) } } } }
}
```

*The output is as follows:*

| ?employee | ?manager       |
|-----------|----------------|
| "John Smyth" | "May Ryan"  |
4.2 Query Rewriting Algorithm

Based on the query rewriting strategies presented in the previous section, we propose a query rewriting algorithm, which ensures that only authorised data is returned by SPARQL 1.1 queries. The algorithm takes as input a query, and a set of quad patterns that need to be filtered out of the query results, and checks each SPARQL graph pattern recursively:

(i) If any of the graph patterns in the outer query match any of the unauthorised quad patterns, a \( \text{FILTER NOT EXISTS} \) element is generated. If the named graph in the query is a variable and the named graph in the authorisation is a constant, then a new graph pattern group is constructed using the named graph from the authorisation and the graph pattern from the query. Otherwise the unchanged graph pattern group from the query is added to the filter. In addition, the constants in the subject, predicate and object positions of the authorisation are bound to the variables in the query using \( \text{FILTER = expression} \). If multiple bindings exist the \( \text{FILTER} \) is generated using the conjunction of the bindings.

(ii) If any of the graph patterns in an inner \( \text{SELECT}, \text{EXISTS FILTER}, \text{NOT EXISTS FILTER} \) or a \( \text{MINUS} \) match any of the unauthorised quad patterns, a \( \text{FILTER NOT EXISTS} \) element is generated as described above and added to the relevant graph pattern group in the subquery or the filter expression.

4.3 SPARQL Updates

SPARQL 1.1 update caters for a number of update operations (\textit{CLEAR}, \textit{LOAD}, \textit{INSERT DATA}, \textit{DELETE DATA} and \textit{DELETE/INSERT}) and a number of graph management operations (\textit{CREATE}, \textit{DROP}, \textit{MOVE}, \textit{COPY} and \textit{ADD}). In the case of update queries there are two possible options: (i) the system should inform the requester that the query cannot be completed and provide a list of the triples that cannot be deleted, inserted etc.; or (ii) the system should behave as if the unauthorised data is not present. If we adopt the first option, the requester will be aware that data exists which they do not have access to, and could potentially infer unauthorised information by issuing one or more additional queries. As a result we adopt the second option and behave as per access control via data filtering. For SPARQL update queries, three distinct query rewriting strategies are required.

**DELETE, INSERT, DELETE/INSERT.** As the \textit{DELETE/INSERT} operation uses graph patterns in order to determine the data to be inserted, deleted or updated, the query rewriting strategy proposed in Section 4.2 is used to filter out unauthorised data.

**DELETE DATA and INSERT DATA.** Given, that the \textit{DELETE DATA} and \textit{INSERT DATA} operations are used to delete and insert specific data, any quads matching an unauthorised quad pattern need to be removed from the query. The query presented in \textit{Query 5} is used to delete all data relating to Joe Bloggs and May Ryan from the \texttt{entx:EmployeeDetails} graph.

\textbf{Query 5 (DELETE authorised data ).} \textit{Given the following query:}
DELETE WHERE { GRAPH entx:EmployeeDetails {
  entx:JBloggs rdf:type foaf:Person .
  entx:JBloggs foaf:name "Joe Bloggs" .
  entx:JBloggs entx:salary 60000 .
  entx:MRyan rdf:type foaf:Person .
  entx:MRyan foaf:name "May Ryan" .
  entx:MRyan entx:salary 33000 . } }

If authorisation 1 in Figure 2 is used to prohibit the requester from deleting May Ryan’s salary, the query is rewritten as follows:

DELETE WHERE { GRAPH entx:EmployeeDetails {
  entx:JBloggs rdf:type foaf:Person .
  entx:JBloggs foaf:name "Joe Bloggs" .
  entx:JBloggs entx:salary 60000 .
  entx:MRyan rdf:type foaf:Person .
  entx:MRyan foaf:name "May Ryan" . } }

After the rewritten query is executed over the dataset presented in Figure 1, the new state of the dataset is as follows:

entx:EmployeeDetails{
  entx:JSmyth rdf:type foaf:Person .
  entx:JSmyth foaf:name "John Smyth" .
  entx:JSmyth entx:salary 33000 .
  entx:MRyan entx:salary 33000 .
}
entx:OrgStructure{
  entx:MRyan entx:worksFor entx:JBloggs .
  entx:JSmyth entx:worksFor entx:MRyan .
}

Graph based update operations. As the CLEAR, DROP, ADD, LOAD, COPY and the MOVE operations work at the graph level, when the requester does not have access to the entire graph these queries need to be rewritten so that they operate at the triple level. For example the CLEAR operation removes all of the data from a target graph. When the requester does not have access to the entire graph, the DELETE operation can be used to only remove authorised data. Query 6 demonstrates how the CLEAR operation can be represented using a DELETE operation.

Query 6 (CLEAR authorised data ). Given the following query:
CLEAR GRAPH entx:EmployeeDetails

If authorisation 1 in Figure 3 is used to prohibit the requester from clearing salary information pertaining to entx:MRyan, the query is rewritten as follows:

DELETE { GRAPH entx:EmployeeDetails { ?s ?p ?o } }
WHERE { GRAPH entx:EmployeeDetails { ?s ?p ?o FILTER NOT EXISTS { GRAPH entx:EmployeeDetails {?s ?p ?o FILTER (?s = entx:MRyan && ?p = entx:salary ) } } } }

After the rewritten query is executed over the dataset presented in Figure 1, the new state of the dataset is as follows:
4.4 Update Rewriting Algorithm

Based on the query rewriting strategies presented in the previous section, we propose an update query rewriting algorithm, which ensures that only authorised data is inserted and deleted. The algorithm takes as input a query, and a set of quads that need to be filtered out of the query results. In the case of:

(i) DELETE/INSERT. The query rewriting algorithm presented in Section 4.2 is used to filter out unauthorised quad patterns.

(ii) DELETE DATA and INSERT DATA. If any of the quads in the query match an unauthorised quad pattern these quads are removed from the query.

(iii) CLEAR and DROP. Negative authorisations pertaining to the specified graph are added as filters to a DELETE query, which is used to ensure that only authorised data is removed from the graph.

(iv) ADD and LOAD. Negative authorisations relating to the source and the destination graphs are added as filters to an INSERT query, which is used to add/load only authorised data to the destination graph.

(v) COPY. A DELETE query which is constructed using negative authorisations matching the destination graph, is used to remove all data from the destination graph. While negative authorisations matching the source and the destination graphs are added as filters to an INSERT query, which is used to copy only authorised data into the destination graph.

(vi) MOVE. The rewriting strategy for the MOVE operation is the same as the COPY operation with an additional DELETE query, constructed using negative authorisations matching the source graph, which is subsequently used to remove authorised data from the source graph.

5 Query Rewriting Evaluation

In Section 3 we formally defined a set of correctness criteria that can be used to compare access control via query rewriting against access control via data filtering. In this section, we demonstrate how the proposed correctness criteria can be used to verify the effectiveness of alternative query rewriting proposals. Given that SPARQL query results are dependent on pattern matching and filtering, in order to prove the correctness of a query rewriting strategy we only have to show it works for all $2^4$ possible combinations of quad patterns for each of the SPARQL 1.1 query types presented in Section 4.4 and Section 4.5. Both the size of the dataset and the data itself are irrelevant. The entire system (test data generator, query rewriting algorithm and model checking algorithm) is implemented in Java, and the query evaluation is performed over an in memory
store using Jena. The Berlin SPARQL Benchmark (BSBM) dataset generator is used to generate a dataset containing 1194 quads. The dataset, queries and authorisations used in the experiments described in this paper can be found at http://correctness.sabrinakirrane.com/.

5.1 Evaluation of SPARQL Query Rewriting

In order to evaluate the different query rewriting strategies we systematically generate authorisations and queries from our auto generated dataset. The following algorithm is used to evaluate each of the auto generated queries:

(i) Firstly, the unauthorised quad pattern is used to remove unauthorised data, and the query is executed against the resulting authorised dataset.

(ii) Secondly, the unauthorised quad pattern is used to rewrite the query based on the query rewriting algorithm and this rewritten query is executed over the dataset which contains both authorised and unauthorised data.

(iii) Finally, the results of both approaches are compared using the criteria presented in Section 3.1.

Existing query rewriting algorithms. Both Chen and Stuckenschmidt [2] and Oulmakhzoune et al. [10] use filters to bind/unbind query solutions based on access control policies that are associated with classes, properties or individuals. Although the authors propose query rewriting strategies for both positive and negative authorisations our evaluation focuses on negative authorisations.

- Chen and Stuckenschmidt [2] use a FILTER != expressions to remove bindings for unauthorised individuals. Whereas OPTIONAL {?s ?p ?o. FILTER (?p=R)} is used to filter matches for a named relation R and OPTIONAL {?s rdf:type ?o. FILTER(?o=C) FILTER(!BOUND (?o))} is used to filter out matches for a named class C.

- Oulmakhzoune et al. [10] also use FILTER != expressions to remove bindings for specific individuals. However, according to their rewriting strategy if access is restricted to the entire triple pattern then the triple pattern is removed. Whereas, if access is partially restricted then the triple pattern is converted to an optional OPTIONAL pattern and the FILTER expression is added to the optional pattern.

As both query rewriting strategies are based on triples as opposed to quads, in order to evaluate we systematically generate authorisations from all 2^3 possible combinations (of constants and variables) for each quad in the auto generated dataset (the graph is always a variable). As the authors focus on BGP, we auto generated queries, composed of either one, two or three RDF quad patterns that are randomly generated from the dataset, for each authorisation.

As the query rewriting strategies proposed by Chen and Stuckenschmidt [2] relies on binding/unbinding constants in the authorisation to variables in the query, when the restricted class, property or individual appears as a constant in the query, it is not possible to generate a binding. In such instances their respective query rewriting strategies fail to satisfy the secure, sound and maximum criteria. Whereas, according to the rewriting strategy proposed by
Oulmakhzoune et al. [10], when access is prohibited to predicates or objects, the relevant triple patterns are made OPTIONAL, which changes the semantics of the query. Although the query does not return any unauthorised data both the sound and maximum criteria are violated.

**Our query rewriting algorithm.** For each RDF quad in the BSBM dataset, we generate $2^4$ authorisations, resulting in a total of 19104 authorisations. As SAMPLE returns different data each time it is executed it is not possible to compare query rewriting to results filtering. Therefore, for each of the authorisations eleven queries are generated as follows:

- **Basic Graph Patterns.** A query is generated, which contains either one, two or three RDF quad patterns, that are randomly generated from data selected from the entire dataset.

- **Aggregates.** For COUNT and GROUP_CONCAT operations, queries are also generated from up to three RDF quad patterns that randomly generated from the entire dataset. Given SUM, MIN, MAX and AVG operations are dependent on numeric data, these queries are generated from a quad pattern which matches all offers (\( ?s \text{ rdf:type bsbm:offer } ?g \)) together with a pattern that matches the associated delivery days (\( ?s \text{ bsbm:deliveryDays } ?o ?g \)).

- **Subqueries and Filters.** A pattern with all variables is added to the outer query, and the inner SELECT, MINUS, FILTER EXISTS and FILTER NOT EXISTS are generated from either one, two or three RDF quad patterns, which are randomly selected from the entire dataset.

In the case of basic graph patterns, aggregates and negation, each of the queries generated from the BSBM dataset were deemed secure, sound and maximum. However, in the case of property paths, given a FILTER NOT EQUALS does not restrict access to the path data, in some instances the algorithm failed to satisfy all three criteria. If we remove the FILTER = binding, the query rewriting strategy is both secure and sound, however it is not maximum. As such, further analysis is required in order to determine a rewriting strategy for property paths.

### 5.2 Evaluation of SPARQL Update Rewriting

For SPARQL updates, the following algorithm is used to evaluate each of the auto generated queries:

(i) Firstly, the unauthorised quad pattern is used to create a dataset which only contains authorised data and a dataset which only contains unauthorised data. The query is subsequently executed against the authorised dataset and both the unauthorised dataset and the updated authorised dataset are merged to form a new merged filtered dataset. In the case of INSERT DATA unauthorised triples need to be removed from the query before it is executed over the authorised dataset. In such instances the filtering approach is quite similar to the rewriting approach.

(ii) Secondly, the quad pattern is used to rewrite the query and this rewritten query is executed over the original dataset.
Finally, the results of both approaches are compared using the criteria presented in Section 3.2.

Our update rewriting algorithm. The query rewriting strategy for LOAD is identical to that for the ADD operation and no rewriting strategy is required for CREATE as access is either granted or denied. Therefore, for each of the authorisations we generate ten different queries as follows:

- **Delete Data and Insert Data.** For DELETE DATA and INSERT DATA, queries are generated from one, two or three RDF quads, that are randomly selected from the entire dataset.

- **Delete, Insert and Delete/Insert.** As per basic graph patterns, DELETE, INSERT and DELETE/INSERT queries are generated from graph patterns that are randomly selected from the entire dataset.

- **Graph Update Operations.** CLEAR, DROP, ADD, COPY and MOVE queries are generated for each graph appearing in the dataset.

As each of the update queries, that were generated from the BSBM dataset, were deemed secure, sound and maximum, we can conclude that the update query processing algorithm is secure, sound and maximum.

6 Conclusion and Future Directions

Although the technology to link web data with other relevant data using machine-readable formats has been in existence for a number of years, in order to support the next generation of eBusiness applications on top of Linked Data appropriate security and privacy mechanisms need to be put in place. When it comes to access control via query rewriting, existing proposals do not consider complex queries that include negation and subqueries, and to the best of our knowledge there is currently no query rewriting strategy for update queries. Also, to date researchers have focused on performance evaluations, as opposed to verifying the correctness of the proposed access control mechanisms.

In this paper, we proposed a query rewriting strategy for both the SPARQL 1.1 queries and updates. We redefined a set of criteria, which was originally used to verify that an access control policy holds over different database states, to allow for access control via query rewriting to be compared against access control via results filtering. We subsequently used the adapted correctness criteria to evaluate the proposed query rewriting algorithms. In future work we plan to devise an appropriate query rewriting strategy for property paths. Based on our initial performance evaluation, which is not presented in the paper, it is evident that FILTER NOT EXISTS can be expensive. As such, we plan to investigate query optimisation techniques for the different SPARQL 1.1 query types and to publish a benchmark that can be used to assess alternative access control strategies.

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