Managing RDF Metadata for Community Webs*

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\textbf{Abstract.} The need for descriptive information, i.e., metadata, about Web resources has been recognized in several application contexts (e.g., digital libraries, portals). The Resource Description Framework (RDF) aims at facilitating the creation and exchange of metadata, as directed labeled graphs serialized in XML. In particular, the definition of schema vocabularies enables the interpretation of semistructured RDF descriptions using taxonomies of node and edge labels. In this paper, we propose (i) a formal model capturing RDF schema constructs; (ii) a declarative query language featuring generalized path expressions for taxonomies of labels (iii) a metadata management architecture for efficient storage and querying of RDF descriptions and schemas.

1 Introduction

Metadata are widely used in order to fully exploit information resources (e.g., sites, documents, data, etc.) available on the WWW \cite{13}. Indeed, metadata permit the description of the content and/or structure of WWW resources in various application contexts: digital libraries, infomediaries, enterprise portals, etc. The Resource Description Framework (RDF) \cite{21} aims at facilitating the creation and exchange of metadata, as any other Web data. More precisely, RDF descriptive (meta)data are represented as \textit{directed labeled graphs} (where nodes are called \textit{resources} and edges are called \textit{properties}) which are serialized using an XML syntax. Furthermore, RDF schema \cite{7} vocabularies are used to define the labels of nodes (called \textit{classes}) and edges (called \textit{property types}) that can be used to describe and query resources in specific user communities. These labels can be organized into appropriate taxonomies, carrying inclusion semantics. In

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this paper, we are focusing on the design of a metadata management system for storing and querying both RDF descriptions and schemas as semistructured data [2].

Our work is motivated by the fact that existing semistructured models (e.g., OEM [23], YAT [12, 11]) cannot capture the semantics of node and edge labels provided by RDF schemas (i.e., taxonomies of classes and property types), while semistructured or XML query languages (e.g., LOREL [4], UnQL [8], StruQL [17], XML-QL [14], XML-GL [10]) are not suited to exploit taxonomies of labels for query evaluation and optimization (i.e., pattern vs. semantic matching of labels). On the other hand, schema query languages as SchemaSQL [20], XSQL [19] or Noodle [22] do provide facilities for querying both schema and data. However, since they are based on common (relational/object-oriented) data models, they also fail to fully accommodate RDF/RDFS features - such as specialization of properties - and also impose strict typing on the data. In this context, we propose RQL, a declarative query language for RDF. RQL relies on a graph data model allowing us to (partially) interpret semistructured RDF descriptions by means of one or more RDF schemas. Thus, RQL adapts the functionality of semistructured query languages to the peculiarities of RDF but also extends this functionality in order to query RDF schemas.

The remainder of this paper makes the following contributions: Section 2, introduces a graph data model capturing RDF schema constructs [21,7]. The originality of our model lies on the distinction between classes and relationship types in the style of ODMG [9], as well as in the introduction of a graph instantiation mechanism, inspired by GRAM [6]. Section 3, presents the RQL language for querying semistructured RDF descriptions and schemas. RQL adopts the syntax and functional approach of OQL [9] while it features generalized path expressions in the style of PQL [3]. The novelty of RQL lies in its ability to query complex semistructured (meta)data and schema graphs using - in a transparent way - taxonomies of labels. Section 4 illustrates how we can benefit from schema information in order to validate and efficiently store RDF descriptions in a DBMS. Finally, section 5 presents conclusions and discusses further research.

2 Towards a Formal Model for RDF

In this section, we briefly recall the main modeling primitives proposed in the RDF Model & Syntax and Schema specifications [21,7] and introduce our graph model (for more details see [18]).

RDF schemas are used to declare classes and property-types, typically authored for a specific community or domain. The upper part of Figure 1 illustrates such a schema for a cultural application. The scope of the declarations is determined by the namespace of the schema, e.g., ns1 (http://www.culture.gr/schema.rdf). Classes and property types are uniquely identified by prefixing their names with their schema namespace, as for example, ns1#Artist or ns1#creates. To simplify our presentation, we hereafter omit the namespace prefixes and denote by C the set of class names and by P the set of property types defined in a schema.
Moreover, classes can be organized into a taxonomy through simple or multiple specialization. The root of this hierarchy, is a built-in class called Resource. For instance, Painter and Painting are subclasses of Artist and Artifact respectively, both specializing Resource. RDF classes do not impose any structure to their objects and class hierarchies simply carry inclusion semantics.

![RDF Data and Schema Diagram]

**Fig. 1.** An example of semistructured RDF data and schemas

RDF property types serve to represent attributes of resources as well as relationships (or roles) between resources. For example, creates defines a relationship between the resource classes Artist (its domain) and Artifact (its range) while fname is an attribute of Artist with type Literal. As we can see in Figure 1, property types may also be refined: paints is a specialization of creates, with its domain and range restricted to the classes Painter and Painting, respectively. We denote by $H = (N, \prec)$, a hierarchy of classes and property types, where $N = C \cup P$. $H$ is well-formed if $\prec$ is a smallest partial ordering such that :

- if $c \in C$ then $c \prec Resource$ (i.e., the root of the class hierarchy).
- if $p_1, p_2 \in P$ and $p_1 \prec p_2$ then domain$(p_1) \prec domain(p_2)$ and range$(p_1) \prec range(p_2)$.

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1 As RDF literals we can have any primitive datatype defined in XML as well as XML markup which is not further interpreted by an RDF processor.
Besides literal and property types, RDF also supports container types, i.e., Bag, Sequence or Alternative. Members of containers are identified by a unique integer index label i, while no restriction is made on their types (i.e., may have heterogeneous member types). RDF classes and container types correspond to schema graph nodes whereas property types correspond to edges.

**Definition 1.** An RDF schema is a directed labeled graph \( RS = (V_S, E_S, \psi, \lambda, H) \) where, \( V_S \) is the set of nodes and \( E_S \) is the set of edges, \( H = (\mathcal{N}, \prec) \) is a well-formed hierarchy of classes and property types (including Bag, Seq, Alt, Literal), \( \lambda \) is a labeling function \( \lambda : V_S \cup E_S \rightarrow \mathcal{N} \), and \( \psi \) is an incidence function \( \psi : E_S \rightarrow V_D \times V_S \), capturing the domain and range of properties.

In RDF, Resources are described through a collection of Statements committing to a schema (see lower part of Figure 1). As a resource we consider anything identifiable by an URL: it may be a Web page (e.g., http://www.museum.gr/picasso.htm), a fragment of a Web page (e.g., http://www.museum.gr/artstyles.xml#cubism) or an entire Web site (e.g., http://www.museum.gr). In the sequel, we denote by \( O \) the set of resource identifiers composed by a namespace and a file name or anchor id (e.g., &ns2#picasso, &ns3#cubism). A non-disjoint population function \( \pi \) assigns to each class \( c \) in \( C \) a set of object identifiers \( \pi(c) \), such that: \( \bigcup \{ \pi(c') \mid c' \prec c \} \subseteq \pi(c) \).

A specific resource together with a named property and its value form an RDF statement, represented by an ordered pair \( < v_1, v_2 > \), where \( v_1 \) is its subject and \( v_2 \) is its object. The subject (e.g., &ns2#picasso) and object (e.g., “Pablo”) should be of a type compatible (under class specialization) with the domain and range of the used predicate (e.g., fnname). Figure 1 shows that RDF properties can be multi-valued (e.g., two paints properties for &ns2#picasso), optional (e.g., there is no fnname property for &ns2#rodin) and they can be inherited (e.g., the creates property of &ns2#rodin). Finally, resources can be multiply classified under several classes (e.g., &ns2#rodin is a Painter and a Sculptor). An RDF statement is simply an edge labeled with a property type, whereas an RDF description introduces a semistructured data graph. The semantics of edge and node labels in this graph is given by one or more associated RDF schemas.

**Definition 2.** Given a population function \( \pi \), an interpretation function is defined as follows:

- for a class \( c \in C \), \( [c] = \pi(c) \) (note that \( [\text{Resource}] = O) \),
- for a property type \( p \in P_r \) \( [p] = \{ < v_1, v_2 > \mid v_1 \in [\text{domain}(p)], v_2 \in \text{range}(p) \} \cup \bigcup_{p' < p} [p'] \),
- for a container type \( [\text{Bag}\text{Seq}\text{Alt}] ) = \{ 1 : v_1, \ldots, n : v_n \} \) where \( v_1, \ldots, v_n \) are values in \( O \).

**Definition 3.** An RDF description, instance of a schema \( RS \), is a directed labeled graph \( RD = (V_D, E_D, \psi, \nu, \tau, O \cup L) \), where: \( V_D \) is a set of nodes and \( E_D \) is a set of edges in an RDF data graph, \( \psi \) is the incidence function \( \psi : E_D \rightarrow V_D \times V_S \), \( \nu \) is a value function \( \nu : V_D \rightarrow O \cup L \) and \( \tau \) is a labeling function \( \tau : V_D \cup E_D \rightarrow N \) which satisfies the following:
– for each node \( v \) in \( V_D \), \( \tau(v) \) is a set of names \( n \in C \cup \{ \text{Literal, Bag, Seq, Alt} \} \) where \( \nu(v) \in [n] \);

– for each edge \( e \) from a node \( v \) to a node \( v' \) in \( E_D \), \( \tau(e) \) is a property type name \( p \in P \cup \{ 1, 2, \ldots \} \), such that \( \nu(v) \in \text{domain}(p) \) and \( \nu(v') \in \text{range}(p) \); additionally, if \( p \in \{ 1, 2, \ldots \} \), \( v \) should be of a container type: \( (Bag|Seq|Alt) \in \tau(v) \).

It should be stressed that our RDF graph model roughly corresponds to a finite, many-sorted relational structure. In fact, besides literal values and resource identifiers, the model relies on relations for class or property extents and containers. Note that resource URIs and names of class or property types may also be considered as values (i.e., strings), denoted as \text{val}. Then, an RDF data graph can be viewed as an instance of the following schema (with unnamed tuples):

\[
\begin{align*}
\text{cls} &\text{(val)} & \text{prop} &\text{(val, val)} & \text{cont} &\text{(val, val, val)} \\
\end{align*}
\]

Here \text{cls}, \text{prop} and \text{cont} correspond to specific schema classes, property types and to the \text{Bag}, \text{Seq}, \text{Alt} container types, respectively. Then \text{prop}(r_1, r_2) indicates that \( r_1, r_2 \) are resource URIs connected through an edge labeled \text{prop}, while \text{cont}(s_1, r_2) indicates that the first member of container value \( s_1 \) is the resource \( r_2 \). RDF schema vocabularies can also be represented using the relations \text{Class} and \text{Property} as well as two additional relations capturing the partial ordering \( (\prec) \) of classes and property types.

3 The RQL Query Language

In this section, we present the language RQL which allows us to query semistructured RDF descriptions using taxonomies of node and edge labels defined in an RDF schema. The following examples depict the use of \text{generalized path expressions} with variables on both kinds of labels.

\textbf{Q1: Find the resources that are classified as both, Painter and Sculptor.}

\[
\begin{align*}
\text{select} &\ X \\
\text{from} &\ X \text{ Painter, Y Sculptor} \\
\text{where} &\ X = Y
\end{align*}
\]

\textbf{Q1} is a simple, OQL-like query, with two variables ranging over sets of nodes. One of the original features of RQL is the ability to also consider property-types as entry-points to a semistructured RDF (meta)data graph. \textbf{Q2} depicts this functionality.

\textbf{Q2: Find the resources that "created" something, and their creations}

\[
\begin{align*}
\text{select} &\ X, Y \\
\text{from} &\ \{X\} \text{creates}\{Y\}
\end{align*}
\]

<table>
<thead>
<tr>
<th>source</th>
<th>target</th>
</tr>
</thead>
<tbody>
<tr>
<td>&amp;rodin</td>
<td>&amp;crucifixion</td>
</tr>
<tr>
<td>&amp;picasso</td>
<td>&amp;guernica</td>
</tr>
<tr>
<td>&amp;picasso</td>
<td>&amp;womanbird</td>
</tr>
<tr>
<td>&amp;claudel</td>
<td>&amp;eternalidol</td>
</tr>
</tbody>
</table>
In Q2, the variables $X$ and $Y$ are range restricted to the source and target (considered as position indices) values of the creates extend (including instances of the sub-properties of creates). We actually treat a property-type as a binary relationship over its domain and range, whose interpretation is a set of ordered tuples. Using these basic constructs, we can now introduce queries on node and edge labels.

**Q3:** Find the resources created by a Painter, which have material “oil on canvas”.

```sql
select Y
from {X:$C}creates{Y}.has_material{Z}
where $C = Painter, Z = “oil on canvas”
```

Q3 essentially implies a navigation through the structure of descriptions and a filtering on both RDF data and schema information. Data variables, like $Y$ and $Z$ are range-restricted to the target and source values respectively of the creates and has_material extents. Schema variables, prefixed with the symbol $\$, are range restricted to the meta-collections Class and Property. In Q3, $\$C$ denotes a class name variable, which is evaluated to the domain (e.g., Artist) of the property creates and its subclasses (e.g., Painter and Sculptor). Then, the first condition in the where clause restricts $\$C$ to Painter. The expression “$X : \$C” (similar to a cast) restricts the source values of the creates extent only to the Painter instances, as for example, &ns2#rodin and &ns2#picasso. Note that if the class name in the where clause is not a valid subclass of the domain of creates, the query will return an empty answer. Moreover, the composition of paths, through the “,” operator in the from clause, implies a join between the extents of creates and has_material on their target and source values respectively. This way, RQL captures the existential semantics of navigation in semistructured data graphs; there exist two “paints” properties for &ns2#picasso while there is no “has_material” property for &ns2#crucifix, created by &ns2#rodin (declared also as a Painter). More formally, Q3 is interpreted as:

\[
\{v_2 | c_1 \in C, c_1 < \text{domain(creates)}, v_1 \in [v_2], v_2 > \in [\text{creates}], v_3 > \in \text{has_material}, c_1 = \text{Painter and } v_3 = \text{”oil on canvas”}\}
\]

RQL can also be used to query RDF schemas, regardless of any underlying instances. The main motivation for this is the use of RQL as a high-level language to implement schema browsing. This is justified by several reasons: a) in real applications RDF schemas may be very large, and therefore they cannot be manipulated in main memory [5]; b) due to class refinement, RDF schemas carry information about the labels of nodes and edges which is only implicitly stated in the schema graph (e.g., by inheritance of properties). Consider, for instance, the following query computing all the outgoing edges of a specific node (or nodes) in the schema graph:

**Q4:** Find all the property types and their corresponding range, which can be used on a resource of type Painter or any of its subclasses.
select $P, $Y
from { $X,$P,$Y }
where $X <= Painter

$P  $Y
creates Artifact
creates Painting
paints Painting

The formal interpretation of Q4 is:
\{ <p, c_2> | \exists p \in P, c_1, c_2 \in C, c_1 \sim domain(p), c_2 \sim range(p), c_1 \sim Painter \}

Some of these edges are explicitly declared in the schema (e.g. paints) while others are inferred from the class hierarchy (e.g. creates). The same is true for the target nodes of the retrieved properties (e.g., Painting and Artifact). It should be stressed that due to multiple classification of nodes (e.g., &ns2#rodin), we can query paths in a data graph (e.g., in Q3) that are not included in the result of the corresponding schema queries (e.g., Q4). Still, the ability of RQL GPEs to combine filtering conditions on both graph data and schema, permits the querying of properties emanating from resources only, according to a specific class hierarchy (e.g., view the properties of &ns2#rodin only as a Painter and not as a Sculptor). As a last example, we illustrate how RQL can be used to express the AboutEachPrefix retrieval function of RDF [21], returning both schema and data information.

Q5: Tell me everything you know about the resources of the site “www.museum.gr”.

<table>
<thead>
<tr>
<th>X</th>
<th>$Z</th>
<th>$P</th>
<th>$Y</th>
<th>$W</th>
</tr>
</thead>
<tbody>
<tr>
<td>$rodin$</td>
<td>Painter</td>
<td>creates</td>
<td>$crucifix$</td>
<td>Painting</td>
</tr>
<tr>
<td>$rodin$</td>
<td>Sculptor</td>
<td>creates</td>
<td>$crucifix$</td>
<td>Painting</td>
</tr>
<tr>
<td>$picasso$</td>
<td>Painter</td>
<td>paints</td>
<td>$guernica$</td>
<td>Painting</td>
</tr>
<tr>
<td>$claude$</td>
<td>Sculptor</td>
<td>sculpts</td>
<td>$eternal$</td>
<td>Sculpture</td>
</tr>
<tr>
<td>$picasso$</td>
<td>Painter</td>
<td>name</td>
<td>Pablo</td>
<td>Literal</td>
</tr>
<tr>
<td>$claude$</td>
<td>Sculptor</td>
<td>name</td>
<td>&quot;Claude&quot;</td>
<td>Literal</td>
</tr>
<tr>
<td>$guernica$</td>
<td>Painting</td>
<td>hasstyle</td>
<td>$cubism$</td>
<td>Style</td>
</tr>
</tbody>
</table>

Q5 will iterate over all property names ($P$), then for each property over its domain ($Z$) and range ($W$) classes and finally over the corresponding extents ($X, Y$). Finally, the result of RQL queries represented in this section in a tabular form (e.g., as –1NF relations) can be naturally captured by RDF Bag containers permitting heterogeneous member sorts (e.g., literals, URIs, sequences). Closure of RQL queries is ensured by supporting access operators for containers [18].

4 The RDF Metadata Management System

The metadata management system currently under development (see Figure 4) comprises three main components: the RDF validator and loader (VRP), the RDF description database (DBMS) and the query language interpreter (RQL).
4.1 Parsing, Validation and Storage

The Validating RDF Parser (VRP) is a tool for analyzing, validating and processing RDF descriptions. Unlike existing RDF parsers (e.g., SiRPAC\textsuperscript{2}), VRP\textsuperscript{3} is based on standard compiler generator tools for Java, namely CUP/JFlex (similar to YACC/Lex). The stream-based parsing support of JFlex and the quick LALR grammar parsing of CUP ensure a good performance, when processing large volumes of RDF descriptions. The most distinctive feature of VRP is its ability to validate RDF descriptions against one or more schemas, as well as the schemas themselves.

![RDF Representation](image)

**Fig. 2.** Example objects in the VRP internal model

The VRP validation module relies on an internal object model implemented in Java, separating RDF schemas from their instances. Instances of those schemas adhere to the graph model presented in section 2. More precisely, the VRP model consists of the following classes (see Figure 3): Resource, RDF.Resource, RDF.Class, RDF.Property, RDF.Container and RDF.Statement. Since, for RDF, everything is a resource, Resource is the root of the class hierarchy of the VRP internal model. Proper instances of this class represent the various resources (e.g., Web pages) in RDF descriptions which are identified by a URI (a hash map is used to transform string URIs to Java object ids). RDF.Resource is a direct subclass of Resource, representing resources with defined RDF/S properties (e.g., rdf:type, rdfs:label, rdfs:seeAlso). The other classes, RDF.Class, RDF.Property, RDF.Container and RDF.Statement,\textsuperscript{4} are subclasses of RDF.Resource. The Java objects representing schema resources are instances of the classes RDF.Class and RDF.

\textsuperscript{2} http://www.w3.org/RDF/Implementations/SiRPAC/
\textsuperscript{3} http://www.ics.forth.gr/proj/isst/RDF
\textsuperscript{4} The RDF.Statement class represents reified statements.
RDF_Property. Figure 2 shows the objects created for the resources ns2#Picasso, ns1#Painter and ns1#paints, from the example of Figure 1.

This representation scheme, compared to the flat representation of triples produced by other RDF parsers, simplifies the manipulation of RDF metadata and schemas to a great extent. Firstly, the classification of resources in hierarchies makes semantics explicit. Moreover, the necessary information for loading such descriptions into a DB is straightforwardly represented in this model. Finally, by separating RDF Schemas from their instances, it allows easier manipulation of schema information, while verification of schema constraints can be performed more efficiently. This separation also facilitates a two-phase loading of schemas and their instances, as described below.

The Loader module APIs are based on the VRP internal model and comprise a number of primitive methods, which can be implemented for various DBMS technologies (e.g., relational, object). These primitive methods are defined as member functions of the classes of the VRP model, for storing the attribute values of the created objects. For example, the method storetype() is defined for the class RDF_Resource, in order to store type information of the objects. The primitive methods of each class are incorporated in a storage method defined in the respective class invoked during the loading process. The Loader takes advantage of the Java method-overriding mechanism, in order to store both RDF descriptions and schemas in a DBMS using a two-phase algorithm: During the first phase, RDF schema information (i.e., class and property descriptions) is loaded in the database, to create the corresponding storage schema. It should be stressed that the storage schema is a direct image of the associated RDFS schemas as presented in section 2. During the second phase, this schema is used to populate the database with resource descriptions. For example, Figure 4 illustrates the representation of RDF descriptions in a relational DBMS, using specific schema information. We should note there is significant current interest
in storing semi-structured data (especially XML data) in RDBMS (e.g., [15]).
Our representation consists of four tables capturing the class and property-type
hierarchies defined in an RDF schema, namely Class, Property, SubClass and
SubProperty. Then, for every new class or property loaded in the database, we
create a new table to store its instances. This implementation conforms to our
graph model and permits a uniform representation of both RDF descriptions
and schemas, while capturing in a precise way the semantics of the latter.

4.2 Query Processing
The RQL interpreter consists of (a) the parser, analyzing the syntax of queries;
(b) the graph constructor, reflecting the semantics of queries and (c) the evaluation
engine, accessing RDF descriptions and schema information from the
underlying database. As in the case of the loader, the RQL evaluation engine
relies on high-level APIs that can be implemented as front-end access functions
for various DBMS technologies. The development of the RQL optimizer is on-
going and will be mainly based on heuristic methods for query rewriting (join
reordering, etc.), making use of realistic assumptions about the queried extents
and exploiting possible index structures. In particular, we plan to implement
indices for RDF schema classes (or property-type) hierarchies (see Subclass and
SubProperty relations) in order to handle efficiently recursive access to all sub-
classes (or subproperties) of a given class (or property).

In applications where the RDF schema contains deep and voluminous classifi-
cation hierarchies, queries accessing subclasses or subproperties of a given class or
property respectively, are extremely time consuming. As demonstrated in [5], in
cultural applications a schema could consist of rather deep and broad taxonomies
of concepts (terms) originating from application specific vocabularies. In [5] the
authors demonstrate the creation of an RDF schema by integrating the rather
shallow ICOM/CIDOC Reference Model [16] and the rich Art & Architecture
Thesaurus [1]. The former is a conceptual schema defined by the International
Council of Museums to describe cultural information, containing around 30 con-
cepts and 60 roles. The latter is one of the largest thesauri in the area of western
art and historical terminology containing around 28,000 terms. In the schema
resulting from the integration of the above conceptual structures, ICOM/CIDOC

Fig. 4. System architecture
concepts and AAT terms are modeled as RDF classes, the latter considered as sub-classes of the former, organised in monohierarchical inheritance taxonomies. Those simple inheritance hierarchies are rather deep and broad and queries that require access to the subtree of a given class or property are essentially traversal queries over the SubClass relation of Figure 4, and are rather costly. The idea is to transform such traversal queries into interval queries on a linear domain, that can be answered efficiently by standard DBMS index structures. To do this, node names are replaced by ids for which a convenient total order exists. An encoding to provide those ids is exposed in detail in [5].

5 Conclusions and Future Work

This paper puts forth the idea that declarative query languages for metadata, like RQL, open new perspectives in the effective and efficient support of WWW applications. RQL can be used as high-level language to access various RDF metadata repositories, by exploiting its ability to uniformly query (meta)data and schema vocabularies and to handle incomplete information. RQL can exploit transparently taxonomies of classes in order to facilitate querying of complex semistructured data using only few abstract labels. The paper also presents an architecture for metadata management comprising efficient mechanisms for parsing and validating RDF descriptions, loading into a DBMS and RQL query processing and optimization.

Current research and development efforts focus on designing appropriate access path selection mechanisms and heuristic methods for query rewriting and optimization. Appropriate index structures for reducing the cost of recursive querying of deep hierarchies need to be devised as well. Specifically, an implementation of hierarchy linearization is under way, exploring alternative node encodings. The performance of the system will be assessed using benchmarks for relational and object-oriented DBMS platforms.

References