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Co-evolution of RDF Datasets

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Abstract. Linking Data initiatives have fostered the publication of large number of RDF datasets in the Linked Open Data (LOD) cloud, as well as the development of query processing infrastructures to access these data in a federated fashion. However, different experimental studies have shown that availability of LOD datasets cannot be always ensured, being RDF data replication required for envisioning *reliable* federated query frameworks. Albeit enhancing data availability, RDF data replication requires synchronization and conflict resolution when replicas and source datasets are allowed to change data over time, i.e., *co-evolution* management needs to be provided to ensure consistency. In this paper, we tackle the problem of RDF data co-evolution and devise an approach for conflict resolution during co-evolution of RDF datasets. Our proposed approach is *property-oriented* and allows for exploiting *semantics* about RDF properties during co-evolution management. The quality of our approach is empirically evaluated in different scenarios on the DBpedia-live dataset. Experimental results suggest that proposed proposed techniques have a *positive impact* on the quality of data in source datasets and replicas.

Key words: Dataset Synchronization, Dataset Co-evolution, Conflict Identification, Conflict Resolution, RDF Dataset

1 Introduction

During the last decade, the Linked Open Data (LOD) cloud has considerably grown [20], comprising currently more than 85 billion triples from approximately 3400 datasets¹. Further, Web based interfaces such as SPARQL endpoints [9] and Linked Data fragments [23], have been developed to access RDF data following the HTTP protocol, while federated query processing frameworks allow users to pose queries against federations of RDF datasets. Nevertheless, empirical studies by Buil-Aranda et al. [6] suggest the lack of Web availability of a large number of LOD datasets, being frequently required the replication of small portions of data, i.e., slices of an RDF dataset, to enhance reliability and performance of Linked Data applications [7]. Although RDF replication allows for enhancing RDF data availability, synchronization problems may be generated because source datasets

¹ Observed on 17th December 2015 on <http://stats.lod2.eu/>.

and replicas *may change* over time, e.g., *DBpedia Live mirror tool*² publishes changes in a public changesets folder³.

Co-evolution refers to mutual propagation of the changes between a replica and its origin or source dataset, where propagation specially in a mutual way, raises synchronization issues which need to be addressed to avoid data inconsistency. Issues are about how changes should be propagated and in case of *inconsistencies* or *data conflicts*, how these conflicts should be resolved. Thus, our main research problem is to develop a co-evolution process able to exploit the properties of RDF data and solve conflicts generated by the propagation of changes among source datasets and replicas. We propose a two-fold co-evolution approach, comprised of the following components: *i*) an RDF data synchronization component, and *ii*) a component for conflict identification and resolution.

Our approach relies on the *assumption* that either the source dataset provides a tool to compute a changeset at real-time or third party tools can be used for this purpose. Another *assumption* is that *slices* of the RDF data from the source dataset are replicated in the replicas or *target datasets*, where a slice⁴ corresponds to an RDF subgraph of the source RDF graph [18].

Figure1 illustrates the co-evolution between two RDF datasets. Initially, a slice of source dataset is used to create a target dataset, i.e., the target dataset T_{t_0} is sliced from the source dataset S_{t_0} of dataset S at time t_0 . Both the source and target datasets evolve themselves with the passage of time, e.g., these datasets evolve to S_{t_j} and T_{t_j} during timeframe $t_i - t_j$, while $t_i < t_j$. Changes from S_{t_j} , denoted by $\delta(S_{t_i-t_j})$, are propagated to the target and vice versa by the RDF data synchronization component. For synchronization, changes from both source and target datasets are compared to identify conflicts. The resolved conflicts are applied on the source and target datasets to vanish inconsistencies, for example, at time point t_j , the co-evolution manager identifies the conflicts and resolves them. The conflicts are resolved and final changes are merged in both datasets.

We empirically evaluate the quality of our co-evolution approach on different co-evolution scenarios of data from the DBpedia⁵ and changesets from DBpedia-live published from September 01, 2015 to October 31, 2015 using iRap [8]. The goal of the evaluation is to study the impact on data quality of the propose co-evolution process, where quality is measured in terms of completeness, consistency, and consciseness [24]. Observed experimental results suggest that our synchronization, and conflict identification and resolution techniques positively affect the quality of the data in both the source and target datasets.

The paper is structured as follows: Section 3 provides formal definitions of the basic notations and concepts used in the proposed co-evolution approach. Section 4 presents detailed problem description and different synchronization strategies. We then present the proposed approach in Section 5 followed by

² <https://github.com/dbpedia/dbpedia-live-mirror>

³ <http://live.dbpedia.org/changesets/>

⁴ An RDF slice is also known as a fragment in the approaches proposed by Ibañez et al. [10], Montoya et al. [15], and Verborgh et al. [23].

⁵ <http://wiki.dbpedia.org/>

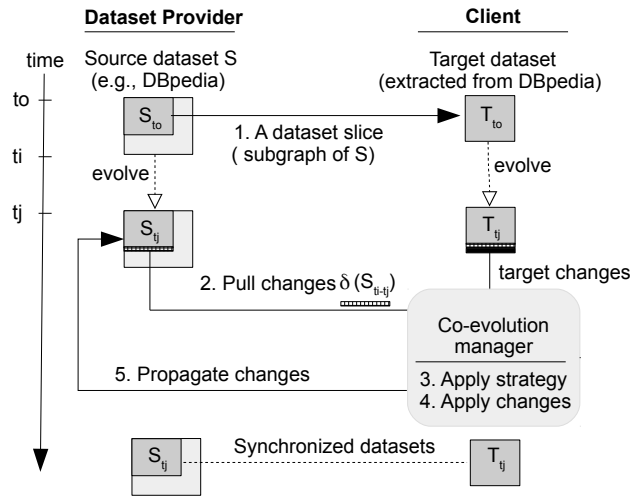


Fig. 1: Co-evolution of linked datasets

evaluation in Section 6. Section 7 presents the related work. We close with the conclusion and the directions for the future work.

2 Motivating example

Let us assume an application which requires information of politicians (e.g., name, birthYear, and spouse). This information can be sliced from the datasets like DBpedia⁶, and used locally by the application. We use the following SPARQL query to slice DBpedia for our use case scenario:

```

CONSTRUCT WHERE {
  ?s    rdf:type      dbo:Politician.
  OPTIONAL {
    ?s    foaf:name    ?name.
    ?s    dbp:birthYear ?birthYear.
    ?s    dbp:spouse   ?spouse.
    ?s    owl:sameAs ?sameAs }
}

```

Our approach is inspired from the scenario described in Figure 2. Initially, at time t_0 , this slice is used to populate target dataset. Both source and target datasets evolve during timeframe $t_i - t_j$, while $t_i < t_j$. Source dataset adds object value $dbo:Agent$ for $rdf:type$, *AdrianSanders* for $foaf:name$, 1959 for $dbp:birthYear$, and *Freebase:AdrianSanders* and <http://wikidata.org/entity/Q479047> for $owl:sameAs$ to resource *dbr:Adrian_Sanders*. Target dataset adds object value $dbo:MemberOfParliament$ for $rdf:type$, *Sanders, Adrian* for $foaf:conname$, and *Freebase:AdrianSanders* and http://yago-knowledge.org/resource/Adrian_Sanders for $owl:sameAs$ to resource *dbr:Adrian_Sanders*.

⁶ <http://dbpedia.org>

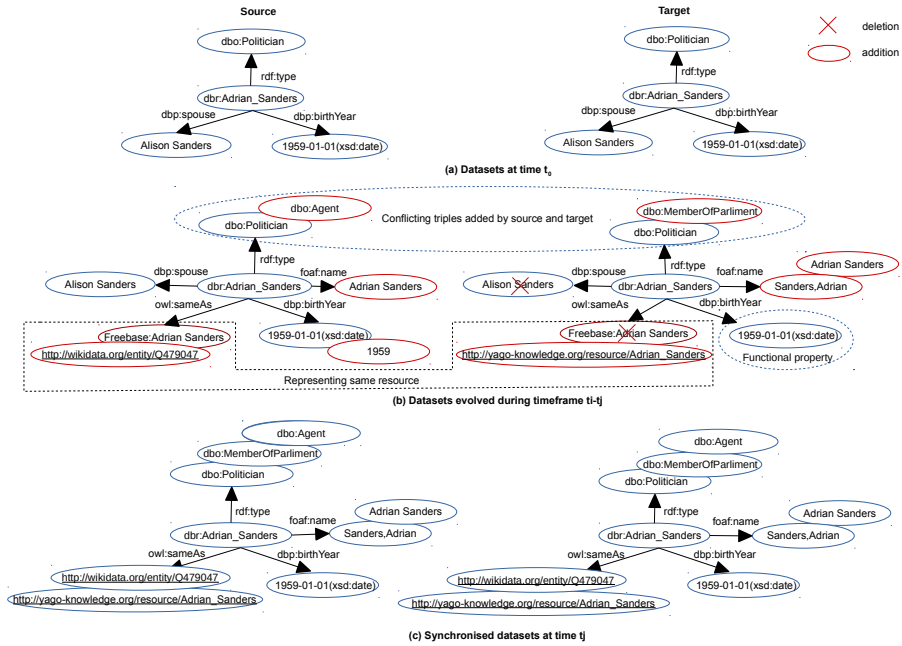


Fig. 2: Motivating example: a) Target dataset initialization, b) evolution, and c) synchronization with source

For resource `dbr:Adrian_Sanders`, we have two different values for `rdf:type` in source and target changesets. We need to check which of them is correct. We already know `dbr:Adrian_Sanders` can be an agent and member of parliament at the same time. However, this check can be made by looking whether the two classes are disjoint or not. Source adds object value `1959` for `dbp:birthYear` to `dbr:Adrian_Sanders`. As `dbp:birthYear` is a functional property, it can have only one value. So, we have to choose one value among the already existing value `1959-01-01` in dataset and the new value `1959` in the changeset. One solution can be to randomly select one value among two. Similarly, source adds object value `Freebase:AdrianSanders` for `owl:sameAs` while target dataset deletes this value after adding it. Considering target as a more customized dataset, we prefer the changes of target over source changes. Thus, we delete `Freebase:AdrianSanders` in synchronized dataset. We still have two different `owl:sameAs` values for `dbr:Adrian_Sanders`. However, as they are representing the same resource, we will keep both values in synchronized dataset.

3 Preliminaries

In this section, we formalize the main concepts required for realizing co-evolution of RDF datasets. The *Resource Description Framework (RDF)*⁷ is widely used to represent information on the Web. A resource can be any thing (either physical or conceptual). The RDF data model expresses statements about Web resources in the form of subject-predicate-object (triple). The subject denotes a resource; the predicate expresses a property of subject or a relationship between the subject and the object; the object is either a resource or literal. For identifying resources, RDF uses Uniform Resource Identifiers (URIs)⁸ and Internationalized Resource Identifier (IRIs)⁹. The rationale behind is that the names of resources must be universally unique. We assume that both source and target datasets are RDF datasets. An RDF dataset is formally defined as follows:

Definition 1 (RDF Dataset). *Formally, an RDF dataset is a finite set of triples $(s, p, o) \in (I \cup B) \times I \times (I \cup L \cup B)$, where $I, B,$ and L are the disjoint sets of all IRIs, blank nodes, and literals [8].*

Let us assume that the slice contains the following triples

dbr:Adrian_Sanders	rdf:type	dbo:Politician;
	dbp:spouse	Alison_Sanders;
	dbp:birthYear	1959-01-01 (xsd:date).

Listing 1.1: Content of initial target dataset

This local copy of sliced dataset, referred as *target dataset*, might undergo changes by user feedback (e.g. user can update the restaurant rating or fulfil abstract information). After some time, DBpedia dataset also evolves by adding new restaurants information or updating the existing ones. As a result, *target dataset* might be out of date and need to be synchronized with DBpedia. During synchronization, a conflict (defined in Definition 5) might occur, if the same information was updated by the source (DBpedia) dataset and the target dataset (by the app users).

Definition 2 (Evolving RDF Dataset). *Let us assume that D_{t_i} represents the version of the RDF dataset D at the particular time t_i . An evolving dataset D is a dataset whose triples change over time. In other words, for timeframe $t_i - t_j$, there is a triple x such as either $(x \in D_{t_i} \wedge x \notin D_{t_j})$ or $(x \notin D_{t_i} \wedge x \in D_{t_j})$.*

Definition 3 (Changeset). *Let us assume that D is an evolving RDF dataset. and D_{t_i} is the version of D at time t_i . A changeset which is denoted by $\delta(D_{t_i-t_j})$ shows the difference of two versions of an evolving RDF dataset in a particular timeframe $t_i - t_j$, while $t_i < t_j$. The changeset is formally defined as $\delta(D_{t_i-t_j}) = \langle \delta(D_{t_i-t_j})^+, \delta(D_{t_i-t_j})^- \rangle$ where,*

⁷ <http://www.w3.org/TR/rdf11-concepts/>

⁸ A URI is a string of characters used as unique identifier for a Web resource.

⁹ A generalization of URIs enabling the use of international character sets.

- $\delta(D_{t_i-t_j})^+$ is a set of triples which have been added to the version D_{t_j} in comparison to the version D_{t_i} .
- $\delta(D_{t_i-t_j})^-$ is a set of triples which have been deleted from the version D_{t_j} in comparison to the version D_{t_i} .

Example 1 (Changesets). Let the following files are found as changesets at time t_i from the source and target datasets.

```
#(A). Deleted triples
#-----
#(B). Added triples
dbr:Adrian_Sanders rdf:type      dbo:Agent;
                   foaf:name     Adrian Sanders;
                   dbp:birthYear 1959;
                   owl:sameAs   Freebase:Adrian Sanders;
                   owl:sameAs   http://wikidata.org/entity/Q479047.
```

Listing 1.2: Source changeset, (A) = $\delta(S_{t_i-t_j})^-$, and (B) = $\delta(S_{t_i-t_j})^+$

```
#(A) Deleted triples
dbr:Adrian_Sanders dbp:spouse   Alison Sanders;
                   owl:sameAs Freebase:Adrian Sanders.
#-----
#(B) Added triples
dbr:Adrian_Sanders rdf:type      dbo:MemberOfParliament;
                   foaf:name     Adrian Sanders;
                   foaf:name     Sanders, Adrian;
                   owl:sameAs   Freebase:Adrian Sanders;
                   owl:sameAs   http://yago-knowledge.org/resource/Adrian_Sanders.
```

Listing 1.3: Target changeset, (A) = $\delta(T_{t_i-t_j})^-$, and (B) = $\delta(T_{t_i-t_j})^+$

Definition 4 (Synchronized Dataset). Two evolving datasets, $D^{(1)}$ and $D^{(2)}$, are said to be synchronized (or in sync) iff one of the following is true at a given time t_k : *i*) $D_{t_k}^{(1)} \subseteq D_{t_k}^{(2)}$, *ii*) $D_{t_k}^{(2)} \subseteq D_{t_k}^{(1)}$, or *iii*) $D_{t_k}^{(1)} \equiv D_{t_k}^{(2)}$.

4 Problem Statement

The core of the co-evolution concept relies on the mutual propagation of changes between the source and target datasets in order to keep the datasets *in sync*. Thus, from time to time, the target dataset and the source dataset have to exchange the changesets and then update the local repositories. Updating a dataset with changesets from the source dataset might cause inconsistencies. Our co-evolution strategy aims at dealing with changesets from either the source or target dataset and provide a suitable reconciliation strategy. Various strategies can be employed for synchronising datasets. In this section we provide requirements and formal definitions for guiding the co-evolution process.

4.1 Synchronization

In the beginning the target dataset is derived (as a slice or excerpt) from the source dataset, thus the following requirement always holds.

Requirement 1 (Initial Inclusion) *At the initial time t_0 , the target dataset T is a subset of the source dataset S : $T_{t_0} \subseteq S_{t_0}$, and thus source and target datasets are in sync.*

After some time, both source and target datasets evolve. At time t_i , the target dataset is $T_{t_i} = T_{t_0} \cup \delta(T_{t_0-t_i})$ and the source dataset is $S_{t_i} = S_{t_0} \cup \delta(S_{t_0-t_i})$.

Requirement 2 (Required Synchronization) *At time t_j , a synchronization of both datasets is required iff source and target datasets were synchronised at time t_i , and the changesets applied to source and target datasets differ, i.e. $\delta(S_{t_i-t_j}) \neq \delta(T_{t_i-t_j})$.*

4.2 Conflict

When we synchronize the target T_{t_i} with source S_{t_i} , there may exist triples which have been changed in both datasets. These changed triples may be conflicting.

Definition 5 (Potential Conflict). *Let us assume that a synchronization is required for a given time slot $t_i - t_j$. $\delta(S_{t_i-t_j})$ is the changeset of the source dataset and $\delta(T_{t_i-t_j})$ is the changeset of the target dataset. A potential conflict is observed when there are triples $x_1 = (s, p, o_1) \in S_{t_j} \wedge x_2 = (s, p, o_2) \in \delta(T_{t_i-t_j}) \wedge x_2 \notin S_{t_j} = S_{t_i} \cup \delta(S_{t_i-t_j})$ with $o_1 \neq o_2$.*

Taking $o_1 \neq o_2$ as an indication for a conflict is subjective; in the sense that the characteristics of the involved property p influences the decision. Consider two triples (s, p, o_1) and (s, p, o_2) . If p is a functional data type property, two triples are conflicting iff the object values o_1 and o_2 are not equal. However, if the property p is a functional object property, these two triples are conflicting if the objects are or can be inferred to be different (e.g. via `owl:differentFrom`). Another property which needs special consideration is `rdf:type`. For this property it is necessary to check whether o_1 and o_2 belong to disjoint classes. Only then these triples would be conflicting. For example, `s1 rdf:type Person` and `s1 rdf:type Athlete` are not conflicting if `Athlete` is a subclass of `Person` (i.e. not disjoint). Thus, the process of detecting conflicts is considering the inherent characteristics of the involved property.

4.3 Synchronization Strategies

In the following, we list possible strategies for synchronization. We consider the time frame $t_i - t_j$, where in the time t_i , the source and target datasets are synchronised and until time t_j , both source and target datasets have been evolving independently. Before applying synchronization, the state of the source dataset is $S_{t_j} = S_{t_i} \cup \delta(S_{t_i-t_j})$ and the target dataset is $T_{t_j} = T_{t_i} \cup \delta(T_{t_i-t_j})$.

Strategy I: This synchronization strategy prefers the source dataset and ignores all local changes on the target dataset; thus, the following requirement is necessary.

Requirement 3 (Inclusion for synchronization) *At any given time t_j , after synchronising using selected strategy, the target dataset should be a subset of the source dataset, i.e. $T_{t_j} \subseteq S_{t_j}$.*

Therefore, the target dataset ignores all triples $\{x \mid x \notin \delta(S_{t_i-t_j}) \wedge x \in \delta(T_{t_i-t_j})\}$ and adds only the triples $\{y \mid y \in \delta(S_{t_i-t_j})\}$. After synchronization, the state of source dataset is $S_{t_j} = S_{t_i} \cup \delta(S_{t_i-t_j})$ and the state of the target dataset is $T_{t_j} = T_{t_i} \cup \delta(S_{t_i-t_j})$. Thus, the requirement 3 is met and $T_{t_j} \subseteq S_{t_j}$. A special case of this strategy is when the target is not evolving.

Example 2. Applying strategy I for synchronization on Example 1 gives the following triples:

dbr:Adrian_Sanders	rdf:type	dbo:Politician;
	rdf:type	dbo:Agent;
	foaf:name	Adrian Sanders;
	dbp:spouse	Alison Sanders;
	dbp:birthYear	1959-01-01 (xsd:date);
	dbp:birthYear	1959;
	owl:sameAs	Freebase:Adrian Sanders;
	owl:sameAs	http://wikidata.org/entity/Q479047 .

Strategy II: With this strategy, the target dataset is not synchronized with the source dataset and keeps all its local changes. Thus, the target dataset is not influenced by any change from the source dataset and evolves locally. After synchronization, at time t_j , the state of the target dataset is $T_{t_j} = T_{t_i} \cup \delta(T_{t_i-t_j})$, and the state of the source dataset is $S_{t_j} = S_{t_i} \cup \delta(S_{t_i-t_j})$. It allows for synchronized replicas only if data is deleted. There is no synchronization if triples in the target dataset are updated or new triples are included.

Example 3. Applying strategy II for synchronization on Example 1 gives the following triples:

dbr:Adrian_Sanders	rdf:type	dbo:Politician;
	rdf:type	dbo:MemberOfParliament;
	foaf:name	Adrian Sanders;
	foaf:name	Sanders, Adrian;
	dbp:birthYear	1959-01-01 (xsd:date);
	owl:sameAs	http://yago-knowledge.org/resource/Adrian_Sanders .

Strategy III: This synchronization strategy respects the changesets of both source and target datasets except that it ignores conflicting triples.

Here, the set of triples in which conflicts occur is $X = \{x_1 = (s, p, o_1) \in S_{t_j} \wedge x_2 = (s, p, o_2) \in \delta(T_{t_i-t_j}) \wedge x_2 \notin S_{t_j} \text{ with } o_1 \neq o_2\}$ ¹⁰. With Strategy

¹⁰ Set of conflicting triples selected after considering the inherent characteristics of the involved property. In rest of the paper, we say potential conflict a conflict, unless otherwise specified.

III, the set of conflicting triples X is removed from the target dataset while the source changeset $\delta(S_{t_i-t_j})$ and the target changeset $\delta(T_{t_i-t_j})$ are added. After synchronization, the state of the source dataset is $S_{t_j} = (S_{t_i} \cup \delta(S_{t_i-t_j}) \cup \delta(T_{t_i-t_j})) \setminus X$ and the state of the target dataset is $T_{t_j} = (T_{t_i} \cup \delta(T_{t_i-t_j}) \cup \delta(S_{t_i-t_j})) \setminus X$. Thus, requirement 3 is met.

Example 4. Applying strategy III for synchronization on Example 1 gives the following triples:

dbr:Adrian_Sanders	rdf:type	dbo:Politician;
	rdf:type	dbo:Agent;
	rdf:type	dbo:MemberOfParliament;
	owl:sameAs	http://wikidata.org/entity/Q479047;
	owl:sameAs	http://yago-knowledge.org/resource/Adrian_Sanders.

Strategy IV: This synchronization strategy also respects the changesets of both source and target datasets. In addition, it includes conflicting triples after resolving the conflicts.

Here, we consider the set of triples in which conflict occurs as $X = \{x_1 = (s, p, o_1) \in S_{t_j} \wedge x_2 = (s, p, o_2) \in \delta(T_{t_i-t_j}) \wedge x_2 \notin S_{t_j} \text{ with } o_1 \neq o_2\}$. The conflicts over these triples should be resolved. It can be resolved using some resolution policy as described in [4]. Table 1 shows a list of various policies for resolving the conflicts. Conflict resolution results in a new set of triples called Y whose triples are originated from X but their conflicts have been resolved. Then, this new set (i.e. Y) is added to the both source and target datasets. After synchronization, the state of the source dataset is $S_{t_j} = ((S_{t_i} \cup \delta(S_{t_i-t_j}) \cup \delta(T_{t_i-t_j})) \setminus X) \cup Y$ and the state of target dataset is $T_{t_j} = ((T_{t_i} \cup \delta(T_{t_i-t_j}) \cup \delta(S_{t_i-t_j})) \setminus X) \cup Y$. Thus, requirement 3 is met.

Example 5. Applying strategy IV for synchronization on Example 1 while resolving the conflicts using function 'Any' gives the following triples:

dbr:Adrian_Sanders	rdf:type	dbo:Politician;
	rdf:type	dbo:Agent;
	rdf:type	dbo:MemberOfParliament;
	foaf:name	Adrian Sanders;
	foaf:name	Sanders, Adrian;
	dbp:birthYear	1959-01-01 (xsd:date);
	owl:sameAs	http://wikidata.org/entity/Q479047;
	owl:sameAs	http://yago-knowledge.org/resource/Adrian_Sanders.

5 Approach

Our approach allows a user to choose a synchronization strategy (as presented in Section 4.3). Below, we describe the status of the source and target datasets after applying each synchronization strategy (see algorithm 1).

Function *CDR* is presented in algorithm 2 which (i) identifies conflicts for the case of strategy III and strategy IV, and then (ii) resolves conflicts only in case of strategy IV. Our approach considers triple-based operations, explained below

Table 1: Conflict resolution policies and functions

Category	Policy	Function	Type	Description
Deciding	Roll the dice	Any	A	Pick random value.
	Reputation	Best source	A	Select the value from the preferred dataset.
	Cry with the wolves	Global vote	A	Select the frequently occurring value for the respective attribute among all entities.
	Keep up-to-date	First*	A	Select the first value in order.
		Latest*	A	Select the most recent value.
	Filter	Threshold*	A	Select the value with a quality score higher than a given threshold.
		Best*	A	Select the value with highest quality score.
TopN*		A	Select the N best values.	
Mediating	Meet in the middle	Standard deviation, variance	N	Apply the corresponding function to get value.
		Average, median	N	Apply the corresponding function to get value.
		Sum	N	Select the sum of all values as the resultant.
Conflict ignorance	Pass it on	Concatenation	A	Concatenate all the values to get the resultant.
Conflict avoidance	Take the information	Longest	S, C, T	Select the longest (non-NULL) value.
		Shortest	S, C, T	Select the shortest (non-NULL) value.
		Max	N	Select the maximum value from all.
		Min	N	Select the minimum value from all.
	Trust your friends	Choose pending*	A	Select the value that belongs to a triple having a specific given value for another given attribute.
		Choose corresponding	A	Select the value that belongs to a triple whose value is already chosen for another given attribute.
		Most complete*	A	Select the value from the dataset (source or target) that has fewest NULLs across all entities for the respective attribute.

* - requires metadata, A - All, S - String, C - Category (i.e., domain values have no order), T - Taxonomy (i.e., domain values have semi-order), N - Numeric.

using seven cases, to identify conflicts. Consider three triples $x_1 = (s, p, o_1)$, $x_2 = (s, p, o_2)$, and $x_3 = (s, p, o_3)$ which are in conflict with each other $x_1 \in \delta(S_{t_i-t_j}) \wedge x_2 \in \delta(T_{t_i-t_j}) \wedge x_3 \in \{\delta(S_{t_i-t_j}) \wedge \delta(T_{t_i-t_j})\} \wedge o_1 \neq o_2 \neq o_3$. In the following we present seven cases of evolution causing conflicts. For the first three cases (I-III), the conflict resolution is straightforward. But for the cases IV-VII, we have to employ a conflict resolution policy to decide about triples x_1 and x_2 :

- **Case I:** x_1 is added to T_{t_j} if x_1 is added by the source dataset and x_2 is deleted from the target dataset: $x_1 \in \delta(S_{t_i-t_j})^+ \wedge x_2 \in \delta(T_{t_i-t_j})^-$.
- **Case II:** x_1 is added to T_{t_j} if x_1 is modified by the source dataset and x_2 is deleted from the target dataset: $x_1 \in \delta(S_{t_i-t_j})^+ \wedge x_2 \in \delta(S_{t_i-t_j})^- \wedge x_2 \in \delta(T_{t_i-t_j})^-$.
- **Case III:** x_2 is added to S_{t_j} if x_1 is deleted from the source dataset and x_2 is modified in the target dataset: $x_1 \in \delta(S_{t_i-t_j})^- \wedge x_2 \in \delta(T_{t_i-t_j})^+ \wedge x_1 \in \delta(T_{t_i-t_j})^-$.
- **Case IV:** if the triple x_1 is added to the source dataset and x_2 is added to the target dataset: $x_1 \in \delta(S_{t_i-t_j})^+ \vee x_2 \in \delta(T_{t_i-t_j})^+$.
- **Case V:** if x_3 is modified by both source and target datasets: $x_2 \in \delta(S_{t_i-t_j})^+ \wedge x_3 \in \delta(S_{t_i-t_j})^- \wedge x_1 \in \delta(T_{t_i-t_j})^+ \wedge x_3 \in \delta(T_{t_i-t_j})^-$.
- **Case VI:** if x_1 is modified by the target dataset: $x_1 \in \delta(S_{t_i-t_j})^+ \wedge x_2 \in \delta(T_{t_i-t_j})^+ \wedge x_1 \in \delta(T_{t_i-t_j})^-$.
- **Case VII:** if x_1 is modified by the source dataset: $x_2 \in \delta(S_{t_i-t_j})^+ \wedge x_1 \in \delta(S_{t_i-t_j})^- \wedge x_1 \in \delta(T_{t_i-t_j})^+$.

```

Data:  $S_{t_i}, T_{t_i}, \delta(T_{t_i-t_j}), \delta(S_{t_i-t_j}), strategy$ 
Result:  $S_{t_j}, T_{t_j}$ 
1 switch strategy do
2   /* Synchronise with the source and ignore local changes */
3   case Strategy I
4     |  $T_{t_j} := T_{t_i} \cup \delta(S_{t_i-t_j}) ;$ 
5     |  $S_{t_j} := S_{t_j} ;$ 
6   end
7   /* Do not synchronise with the source and keep local changes */
8   case Strategy II
9     |  $T_{t_j} := T_{t_i} \cup \delta(T_{t_i-t_j}) ;$ 
10    |  $S_{t_j} := S_{t_i} \cup \delta(S_{t_i-t_j}) ;$ 
11  end
12  /* Synchronise with the source and target datasets and ignore conflicts */
13  case Strategy III
14    |  $S_{t_j}, T_{t_j} := CDR(\delta(S_{t_i-t_j}), \delta(T_{t_i-t_j}), T_{t_i}, false) ;$ 
15  end
16  /* Synchronise with the source and target datasets and resolve the conflicts */
17  case Strategy IV
18    |  $S_{t_j}, T_{t_j} := CDR(\delta(S_{t_i-t_j}), \delta(T_{t_i-t_j}), T_{t_i}, true) ;$ 
19  end
20 endsw

```

Algorithm 1: Updating the source and target datasets by the chosen synchronization strategy.

Algorithm 2 shows the pseudocode of the procedure for updating the source and target datasets at the end of each timeframe. The function `resolveConflict` identifies operations described in Case I-VII. In addition, for the cases IV-VII, it resolves conflicts based on the type of involved predicate. As we discussed earlier, whether a conflict between two triple exists depends heavily on the type of property. Consider two triples (s, p, o_1) and (s, p, o_2) , if p is `rdfs:label`, we measure the similarity between o_1 and o_2 using the Levenshtein distance. We pick both values of `rdfs:label` if their similarity is below a certain threshold otherwise we treat them as conflicting. The function `resolveConflict` identifies operations containing deleted in the source, deleted/added/modified in the target dataset. In case of deleted in the source dataset and added/modified by the target dataset, it returns a triple to be added in T_{t_j} otherwise null.

Figure 3 illustrates algorithm 2 for updating the target dataset T_{t_i} . We choose the synchronization strategy IV for the synchronization task. In the first step, we use a tree structure to identify conflicts for the triples in $\delta(S_{t_i-t_j})^+$. Consider the tree structure (a) in *step*₁ for the triple $(dbr : Adrian_Sanders, rdf : type, dbo : Agent)$. We find different object values for $(dbr : Adrian_Sanders, rdf : type)$ in $\delta(S_{t_i-t_j})^+, \delta(T_{t_i-t_j})^+$, and T_{t_i} . Then, we identify the triple based operation. For example, if we find the object value $dbo : Agent$ in $\delta(S_{t_i-t_j})^+, dbo : MemberOfParliament$ in $\delta(T_{t_i-t_j})^+$, and $dbo : Politician$ in T_{t_i} , it represents case IV of addition by both source and target. Thus, this case represents a potential conflicting triple. We check if the values in $T_{t_i}, \delta(S_{t_i-t_j})^+$ and $\delta(T_{t_i-t_j})^+$ are disjoint for predicate `rdf:type`. As $dbo : Politician, dbo : Agent,$ and $dbo : MemberOfParliament$ are not disjoint, we pick all these values.

```

Data:  $S_{t_i}, T_{t_i}, \delta(T_{t_i-t_j}), \delta(S_{t_i-t_j}), \text{conflictresolution}$ 
Result:  $S_{t_j}, T_{t_j}$ 
1  $T_{t_j} = \phi$ ;
2  $S_{t_j} = \phi$ ;
3  $temp = \phi$ ;
4 /* step1 */
5 for all triples  $x_1 = (s_1, p_1, o_1) \in \delta(S_{t_i-t_j})^+$  do
6     /* finding triples which are in conflict with  $x_1$  */
7      $X = \{x_2 = (s_1, p_1, \text{Node.ANY}) \in \delta(S_{t_i-t_j})^- \cup \delta(T_{t_i-t_j})^+ \cup \delta(T_{t_i-t_j})^- \cup T_{t_i}\}$ ;
8     if  $X = \phi$  then
9         |  $temp = temp \cup x_1$ ;
10    end
11    else
12        |  $x = \text{resolveConflict}(x_1, X)$ ;
13        |  $temp = temp \cup x$ ;
14    end
15 end
16 /* step2 */
17  $T_{t_i} := T_{t_i} \setminus \delta(T_{t_i-t_j})^- \cup \delta(S_{t_i-t_j})^-$ ;
18  $S_{t_i} := S_{t_i} \setminus \delta(T_{t_i-t_j})^- \cup \delta(S_{t_i-t_j})^-$ ;
19 /* step3 */
20  $temp := temp \cup \delta(S_{t_i-t_j})^+ \cup \delta(T_{t_i-t_j})^+$ ;
21 /* Updating the target dataset */
22  $T_{t_j} := T_{t_i} \cup temp$ ;
23 /* Updating the source dataset */
24  $S_{t_j} := S_{t_i} \cup temp$ ;

```

Algorithm 2: CDR algorithm: Conflict Detection and Resolution

Now, consider the tree structure (b) in $step_1$ for triple ($dbr : \text{Adrian_Sanders}$, $owl : \text{sameAs}$, $http : // \text{wikidata.org/entity/Q479047}$). It also represents case IV of addition by both source and target. The triple ($dbr : \text{Adrian_Sanders}$, $owl : \text{sameAs}$, $\text{Freebase} : \text{AdrianSanders}$) is added by source but deleted by target. Considering the target as more customized dataset, we give preference to target change. The tree structure (c) in $step_1$ for the triple ($dbr : \text{Adrian_Sanders}$, $dbp : \text{birthYear}$, 1959). It is also handled in case IV. As $dbp:\text{birthYear}$ is functional property, we select only one value among already existing value and the new value using resolution function 'Any'.

Furthermore, the user has the opportunity to adopt the manual or automatic selection of resolution functions. The resolution function is oriented to the type of predicates. The list of supported resolution functions is shown in Table 1. For automatic selection of conflict resolution functions for predicates, we check attributes of predicates (e.g., type, cardinality). Based on the usage analysis of different functions in [4], we prefer functions such as first, longest, and maximum for resolving conflicts. For instance, we prefer function longest for strings to avoid loss of information. For numeric data types, we prefer function max to keep the up-to-date value. For URIs, we pick the first value.

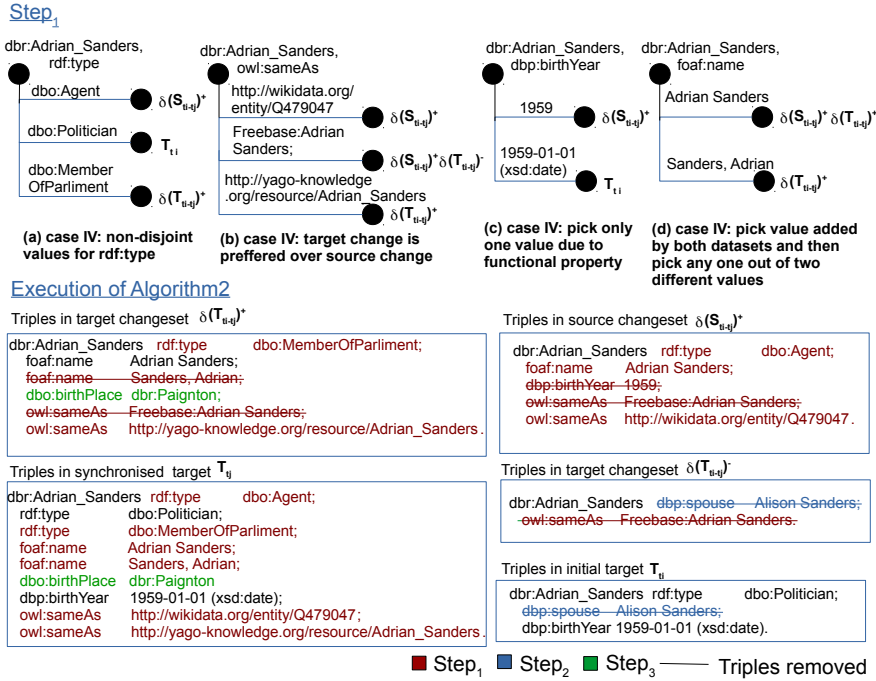


Fig. 3: Execution of algorithm 2 to synchronize T_{t_i} with S_{t_i}

6 Evaluation

In order to assess the discussed approaches for synchronization and conflict identification/resolution, we prepare a testbed based on a slice of DBpedia using the following SPARQL query.

```

CONSTRUCT WHERE {
  ?s a          Politician ;
    foaf:name   ?name ;
    dbo:nationality ?nationality ;
    dbo:abstract ?abstract ;
    dbp:party   ?party ;
    dbp:office  ?office
  OPTIONAL { ?s foaf:depiction ?depiction }
}

```

The extracted dataset is used as the initial source and target dataset. Then, we collect a series of changesets from DBpedia-live published from September 01, 2015 to October 31, 2015 using iRap [8]. We found a total of 304 changesets. These changesets are leveraged to simulate updates of the source and target datasets. We randomly select a total of 91 addition parts of changesets and altered values of their triples. Table 2 provides the number of triples of initial target, source and their associated changesets before synchronization. Initially, we have 200082 triples with 163114 unique objects in T_{t_i} where $t_i = \text{September}01, 2015$.

Table 2: Number of triples in the source, target, and changesets for a given timeframe

S_{t_i}	T_{t_i}	$\delta(S_{t_i-t_j})^+$	$\delta(S_{t_i-t_j})^-$	$\delta(T_{t_i-t_j})^+$	$\delta(T_{t_i-t_j})^-$
200082	200082	948	160	11725	81

Given a timeframe $t_i - t_j$ ¹¹, the goal is to synchronize source and target datasets. To do that, we define five different scenarios. In four scenarios, we apply subsequently the strategy (I-IV) over all predicates of the changesets and measure the performance. For the last scenario, we apply two strategies in a combined form on the changesets where we select strategy IV for predicate *dbp:office*, and strategy I for predicates *dbp:party*, *dbo:nationality*, *rdf:type*, *foaf:name*, *dbo:abstract*, and *foaf:depiction*. For all predicates using strategy IV, we select the resolution function 'any'. Table 3 provides the number of triples produced as a result of synchronizing S_{t_i} and T_{t_i} in each scenario. The updated changesets are sent back to the source and target for synchronization purpose. The number of conflicting triples found in scenarios 3, 4, and 5 are shown in Table 3.

Table 3: Results of synchronization

Scenario	$\delta(S_{t_i-t_j})^+$	$\delta(S_{t_i-t_j})^-$	$\delta(T_{t_i-t_j})^+$	$\delta(T_{t_i-t_j})^-$	Conflicting triples	RunTime (seconds)
1	0	0	948	160	-	0.0
2	0	0	11725	81	-	0.0
3	11682	81	12060	81	343	0.5
4	11800	195	12186	81	343	2.0
5	5227	131	6081	121	186	0.2

The running time of the five different scenarios is also shown in Table 3 (These times are recorded only for the execution of synchronization part and do not include data loading time). Evaluation showed that strategy IV (performed in scenario IV) needs more time even from strategy III (performed in scenario III) where all conflicts were detected but not resolved.

Synchronization influences data quality specially in terms of data consistency. To evaluate the usefulness of the synchronization approach, we use three data quality metrics i.e. (1) *completeness*, (2) *conciseness*, and (3) *consistency* described as follows:

1. Completeness refers to the degree to which all required information is present in a dataset [24]. We measure it for source and target changesets to identify which helps more in completeness. We measure it using

$$\frac{\text{Number of unique triples in synchronised dataset}}{\text{Number of unique triples in (initial dataset } \cup \text{ changeset)}}$$

2. Consistency states that the values should not be conflicting. We measure it using

$$\frac{\text{Number of non-conflicting triples in synchronized dataset}}{\text{Number of triples in (initial dataset } \cup \text{ source and target changesets)}}$$

3. Conciseness measures the degree to which the dataset does not contain redundant information using

$$\frac{\text{Number of unique triples in dataset}}{\text{Number of all triples in dataset}}$$

¹¹ 09/01/2015-10/31/2015.

Conciseness (before synchronization) is computed using initial target dataset and source and target changesets. We compute these metrics for all the assumed scenarios, the results are shown in Table 4. For our sample case study, we found almost equal contribution of both source and target changesets in reducing the missing information. However, we found minimum *163191* number of unique objects using strategy II and maximum *163591* number of unique objects using strategy IV. Please note that strategy 1 and strategy II may not necessarily increase the number of unique triples as they do not consider about conflicts. It can be observed by analyzing the scenario 1 where the role of source changesets in completeness is 99% which is less than the target contribution. Through evaluation, we found significant increase in conciseness for all strategies.

Table 4: Synchronization effect on completeness, consistency, and conciseness

Scenario	Completeness (source)	Completeness (target)	Consistency	Conciseness (before synchronization)	Conciseness (after synchronization)
1	99%	100%	-	77%	81%
2	99%	99%	-	77%	81%
3	99%	100%	94%	77%	81%
4	99%	100%	94%	77%	81%
5	99%	100%	-	77%	81%

7 Related Work

Related work includes synchronization of semantic stores for concurrent updates by autonomous clients [1], synchronization of source and target [22], replication of partial RDF graphs [19], ontology change management [12], and conflict resolution for data integration [3–5, 11, 13, 14, 16, 17, 21]. We discuss related work here along the dimensions change management and conflict resolution.

7.1 Change management

Efficient synchronization of semantic stores is challenging due to the factors, scalability and number of autonomous participants using replica. *C-Set* [1] is a Commutative Replicated Data Type (CRDT) that allows concurrent operations to be commutative and thus, avoids other integration algorithms for consistency. The approach, proposed in [19], allows to replicate part of an RDF graph on clients. Clients can apply offline changes to this partial replica and write-back to original data source upon reconnection. Table 5 provides a comparative analysis of change management approaches used for synchronization.

A few surveyed approaches [2, 12] are related to ontological change management. In [12], a framework is developed for ontology change management and tested for RDF ontologies. This framework allows to design ontology evolution algorithms. In [2], an approach for the versioning and evolution of ontologies, based on RDF data model, is presented. It considers atomic changes such as addition or deletion of statement and then aggregates them to compound changes to form a change hierarchy. This change hierarchy allows human reviewers to analyze at various levels of details.

7.2 Conflict resolution

For relational databases, there is much work on inconsistency resolution [3,4,16]. The *Humboldt Merger* [3], extension to SQL with a FUSE BY statement, resolves conflicts at runtime. *Fusionplex* [16] integrates data from heterogeneous data sources and resolves inconsistencies during data fusion. For fusion, it uses parameters such as user-defined data utility, threshold of acceptance, fusion functions, and metadata. [4] classifies conflict resolution strategies into three classes: ignorance, avoidance, and resolution. Conflict ignorance strategies are not aware of conflicts in the data. Conflict avoidance strategies are aware of whether and how to handle inconsistent data. Conflict resolution strategies may use metadata to resolve conflicts. These can be divided into deciding and mediating. A deciding strategy chooses value from already existing values whereas a mediating strategy may compute a new value.

Sieve Fusion Policy Learner [5] uses a gold standard dataset to learn optimal fusion function for each property. The user specifies possible conflict resolution strategies from which the learning algorithm selects the one that gives maximum results within error threshold with respect to the gold standard.

Most relevant approaches to our proposed work are *Sieve* [13] - part of *Linked Data integration framework (LDIF)* [21], data fusion algorithm [14] for *OD-CleanStore* [11], *RDFSsync* [22], and *Col-graph* [10]. Our approach differs from the previous ones in the scope of the problem (see Figure 4). RDFSsync performs synchronization of two datasets by merging both graphs, deleting information which is not known by source, or making the target equal to source. In contrast to RDFSsync, our co-evolution approach allows merging of both graphs while ignoring or resolving conflicts and keeping only source or target changes. Col-graph deals with consistent synchronization of replicas and does not tackle conflicts.

Sieve and ODCS are data fusion approaches and thus, are applicable where described data have different schemata. In contrast to both, co-evolution approach is applicable where described data have same schemata. Both approaches define conflicts as RDF triples sharing same subject/predicate with inconsistent values for objects. Sieve uses quality scores to resolve data while, ODCS produces quality scores of resolved data and keeps name of dataset from where the resolved value belongs. We extend the conflict definition by further considering the predicate type, as discussed earlier (see Definition 5).

Table 5: Synchronization approaches

Approach	Synchronization	Bi-directional	Participants	Conflict handling*
<i>C-Set</i>	✓	✓	n	x
<i>RDFSsync</i>	✓	x	source, target	x
<i>Col-graph</i>	✓	✓	n	x
[14]	✓	back to source	n	x
<i>Co-evolution</i>	✓	✓	source, target	✓

* - Triple level conflicts according to Definition 5

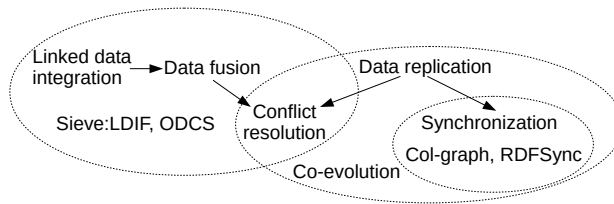


Fig. 4: How co-evolution fits with state-of-the-art

8 Conclusion and Future Work

In this paper we presented an approach to deal with co-evolution which refers to mutual propagation of the changes between a replica and its origin dataset. Using the co-evolution process, we address synchronization and conflict resolution issues. We demonstrated the approach using formal definitions of all the concepts required for realizing co-evolution of RDF datasets and implemented it using different strategies. We evaluated the approach using data quality metrics completeness, conciseness, and consistency. A thorough evaluation of the approach, using DBpedia changesets, indicates that our method can significantly improve the quality of dataset. In the future, we will extend the concept of conflict resolution at schema level. For example, renaming a class invalidates all triples that belong to it in a dataset. Further, we will evaluate the scalability and performance of our proposed approach using a benchmark dataset.

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