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Introducing a Python library to perform time-agnostic queries on datasets compliant with the OpenCitations' provenance model.

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4.1 PROVENANCE FOR THE SEMANTIC WEB

In his book *Weaving the Web: the original design and ultimate destiny of the World Wide Web*, Tim Berners Lee, the inventor of the WWW, states:

> *I have a dream for the Web [in which computers] become capable of analyzing all the data on the Web – the content, links, and transactions between people and computers. A "Semantic Web", which makes this possible, has yet to emerge, but when it does, the day-to-day mechanisms of trade, bureaucracy and our daily lives will be handled by machines talking to machines. The "intelligent agents" people have touted for ages will finally materialize.* (Berners-Lee, Weaving the Web: the original design and ultimate destiny of the World Wide Web 1999)

In this vision, which represents the first formulation of the Semantic Web, it is already possible to identify the criticality that would have led to discuss the provenance topic in the following years. The data must be reliable in a world where automatic data analysis systems manage trade, bureaucracy, and daily lives. However, the Web is an open and inclusive dimension in which it is possible to find contradictory and questionable information. Therefore, it is essential to own indications such as the primary data source, who created or modified it, and when that happened. However, the underlying technologies of the Semantic Web (RDF, OWL, SPARQL) were not originally intended to express such information.

In order to revise state of the art and develop a roadmap on provenance for Semantic Web technologies, the Provenance Incubator Group (Provenance Incubator Group Charter 2010) was established in 2010. One of the first problems was identifying a shared and universal definition of "provenance", a task that proved impossible given its broad and multisectoral nature. Therefore, a working definition was accepted, restricted the context of the Web:

> *Provenance of a resource is a record that describes entities and processes involved in producing and delivering or otherwise influencing that resource. Provenance provides a critical foundation for assessing authenticity, enabling trust, and allowing reproducibility. Provenance assertions are a form of contextual metadata and can themselves become important records with their own provenance.* (Gil, Cheney, et al. 08 December 2010)

Starting from this working definition, the group has compiled 33 use cases to formulate scenarios and requirements. Topics covered included eScience, eGovernment, business, manufacturing, cultural heritage, and library science, to name a few. The analysis of these use cases led to the elaboration of three scenarios: a news aggregator, the study of an epidemic, and a business contract. The second scenario, the study of the epidemic, is particularly interesting for the case study of this work because it focuses on the reuse of scientific data. Alice is an epidemiologist studying the spread of a new disease called owl flu. Alice needs to integrate structured and unstructured data from different sources, to understand how data has evolved through provenance and version information. In addition, she needs to justify the results obtained by supporting the validity of the sources used, reusing data published by others in a new context, and using the provenance to repeat previous analyses with new data. Introducing the problem with a concrete and complex example is helpful to understand how multifaceted and multidimensional it is. Specifically, provenance can be evaluated under three categories: content, management, and usage, each with various dimensions summarised in Table 1.

Category	**Dimension**	**Description**
Content	Object	The artifact that a provenance statement is about.
	Attribution	The sources or entities that contributed to creating the artifact in question.
	Process	The activities (or steps) that were carried out to generate or access the artifact at hand.
	Versioning	Records of changes to an artifact over Time and what entities and processes were associated with those changes.
	Justification	Documentation recording why and how a particular decision is made.
	Entailment	Explanations showing how facts were derived from other facts.
Management	Publication	Making provenance available on the Web.
	Access	The ability to find the provenance for a particular artifact.
	Dissemination	Defining how provenance should be distributed and its access be controlled.
	Scale	Dealing with large amounts of provenance.
Use	Understanding	How to enable the end-user consumption of provenance.

	Interoperability	Combining provenance produced by multiple different systems.
	Comparison	Comparing artifacts through their provenance.
	Accountability	Using provenance to assign credit or blame.
	Trust	Using provenance to make trust judgments.
	Imperfections	Dealing with imperfections in provenance records.
	Debugging	Using provenance to detect bugs or failures of processes.

Table 1 Dimensions of provenance

Many data models, annotation frameworks, vocabularies, and ontologies have been introduced to meet the above requirements. A complete list of all existing strategies will be drawn up in section 4.2, and their advantages and disadvantages will be explained.

4.2 REPRESENTING PROVENANCE IN RDF

The landscape of strategies to formally represent provenance in RDF data is vast and fragmented (Table 2). There are many approaches varying in semantics, tuple typology, standard compliance, dependence on external vocabulary, blank node management, granularity, and scalability. For an in-depth study of this topic, consult the article *Provenance-Aware Knowledge Representation: A Survey of Data Models and Contextualized Knowledge Graphs* (Sikos and Philp 2020). First, the annotation syntaxes and, subsequently, the knowledge organization systems related to provenance will be discussed in sections 4.2.1 and 4.2.2.

Type of approach	**Metadata Representation Models**
Quadruples	Named graphs, RDF/S graphsets, RDF triple coloring
Extension of the RDF data model	Notation 3 Logic, RDF^{+}, annotated RDF (aRDF) and Annotated RDF Schema, SPOTL(X), RDF*
Encapsulating Provenance with RDF Triples	PaCE, singleton property
Data models alternative to RDF	GSMM, mapping entities to vectors
Knowledge organization system	OPM, PML, Provenir, PREMIS, SWAN, DC, PROV, OCDM

Table 2 Annotation frameworks for RDF provenance

4.2.1 METADATA REPRESENTATION MODELS FOR RDF PROVENANCE

To date, the only standard syntax for annotating triples' provenance is *RDF reification* and is the only one to be compatible with all RDF-based systems. Included since RDF 1.0 (RDF Primer 2004), it consists in associating a statement to a new node of type *rdf:Statement*, which is connected to the triple by the predicates *rdf:subject*, *rdf:predicate*, and *rdf:object*. For example, consider the statement (*exproducts:item10245*, *exterms:weight*, *"2.4" xsd:decimal*) (Figure 1). Using the reification vocabulary, a new node *exproducts:triple12345* is introduced and associated with the following properties:

- (*exproducts:triple12345*, *rdf:type*, *rdf:Statement*)
- (*exproducts:triple12345*, *rdf:subject*, *exproducts:item10245*)
- (*exproducts:triple12345*, *rdf:predicate*, *exterms:weight*)
- (*exproducts:*item10245, rdf*:object*, *"2.4" xsd:decimal*).

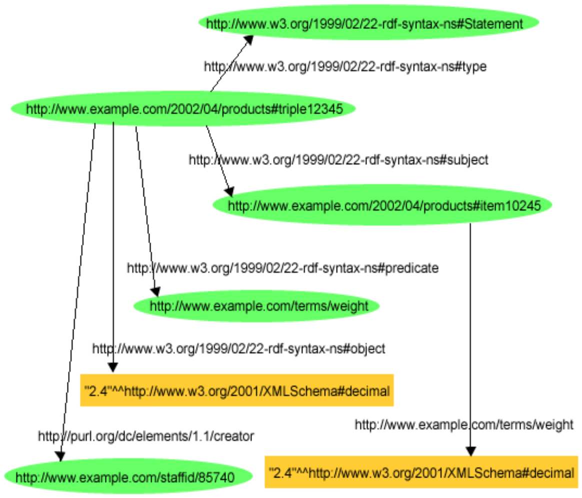

http://www.w3.org/1999/02/22-rdf-syntax-ns#Statement
http://www.w3.org/1999/02/22-rdf-syntax-ns#type
http://www.example.com/2002/04/products#triple12345
http://www.w3.org/1999/02/22-rdf-syntax-ns#subject
http://www.example.com/2002/04/products#item10245
http://www.w3.org/1999/02/22-rdf-syntax-ns#predicate
http://www.example.com/terms/weight
http://www.w3.org/1999/02/22-rdf-syntax-ns#object
"2.4"^^http://www.w3.org/2001/XMLSchema#decimal
http://purl.org/dc/elements/1.1/creator
http://www.example.com/terms/weight
http://www.example.com/staffid/85740
"2.4"^^http://www.w3.org/2001/XMLSchema#decimal

Figure 1 A statement, its reification, and its attribution

Finally, this new URI can become the subject of new provenance triples, as the responsible agent, expressed through the property (*exproducts:item10245*, *dc:creator*, *exstaff:85740*).

Such methodology has a considerable disadvantage: the size of the dataset is at least quadrupled since subject, predicate, and object must be repeated to add at least one provenance's information. There is a shorthand notation, the rdf:ID attribute in RDF/XML (Figure 2), but it is not present in other serializations.

```
<?xml version="1.0"?>
<!DOCTYPE rdf:RDF [<!ENTITY xsd "http://www.w3.org/2001/XMLSchema#">]>
<rdf:RDF
   xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
   xmlns:dc="http://purl.org/dc/elements/1.1/"
   xmlns:exterms="http://www.example.com/terms/"
   xml:base="http://www.example.com/2002/04/products">
   <rdf:Description rdf:ID="item10245">
      <exterms:weight rdf:ID="triple12345" rdf:datatype="&xsd;decimal">
                 2.4
          </exterms:weight>
   </rdf:Description>
   <rdf:Description rdf:about="#triple12345">
      <dc:creator rdf:resource="http://www.example.com/staffid/85740"/>
   </rdf:Description>
</rdf:RDF>
```

Figure 2 Generating reifications using rdf:ID

Finally, composing SPARQL queries to obtain provenance annotated through *RDF Reification* is cumbersome: to identify the URI of the reification, it is necessary to explicit the entire reference triple. For all the mentioned reasons, there are several deprecation proposals for this syntax, including that by David Beckett, one of the editors of RDF in 2004, and RDF/XML (Revised) W3C Recommendation:

> *There are a few RDF model parts that should be deprecated (or removed if that seems possible), in particular reification which turned out not to be widely used, understood or implemented even in the RDF 2004 update* (Beckett 2010).

After *RDF Reification*, in 2006, the W3C published a note that suggested a new approach to express provenance, called *n-ary relations* (Defining N-ary Relations on the Semantic Web 2006). In RDF and OWL, properties are always binary relationships between two URIs or a URI and a value. However, sometimes it is convenient to connect a URI to more than one other URI or value, such as expressing the provenance of a certain relationship. The *n-ary relations* allow this behavior through the instance of a relationship in the form of a blank node. Taking the above example, (*exproducts:item10245, exterms:weight, "2.4" xsd:decimal*) becomes (*exproducts:item10245, exterms:weight*, *_:Weight*). Then, *_:Weight* can be associated with the value by (*_:Weight, exterms:weight*, *"2.4"xsd:decimal*), and to the provenance by (*_:Weight, dc:creator, exstaff:85740*). From an ontological point of view, the *_:Weight* class is a "reified relationship". Therefore, there is a clear similarity between *n-ary relations* and *RDF Reification,* with the difference that the latter reifies the statement, the first the predicate, with the advantage of not having to repeat all the triple elements but only the predicate. The second similarity, which is the main disadvantage of *n-ary relations*, is introducing blank nodes, which cannot be globally dereferenced.

In summary, *RDF Reification* and *n-ary relations* are the only standard and the only alternative recommended by W3C to describe the provenance in RDF and have fatal design flaws. For this reason, different approaches have been proposed since 2005, starting with Named Graphs and *formulae* in Notation 3 Logic, as will be clarified in the following paragraphs.

Named Graphs are graphs associated with a name in the form of a URI. They allow RDF statements describing graphs, with multiple advantages in numerous applications. For example, in Semantic Web publishing, named graphs allow a publisher to sign its graphs so that different information consumers can select specific graphs based on task-specific trust policies. Different tasks require different levels of trust. A naive information consumer may, for example, decide to accept any graph, thus collecting more information as well as false information. Instead, a more cautious consumer may require only graphs signed by known publishers, collecting less but more accurate data (Carroll, et al. 2005). From a syntactical point of view, named graphs are quadruples, where the fourth element is the graph URI that acts as context to triples. It is a solution compatible with the RDF data model, does not rely on terms or ontologies to capture the provenance, does not cause *triple bloat*, and is scalable and suitable for Big Data applications. On the other hand, concerning serialization, it is possible to implement named graphs using extensions of RDF/XML, Turtle, and N-Triples, called TriX, TriG, and N-Quads, all standardized and compatible with the SPARQL algebra.

The above advantages have led the Web Alliance to propose named graphs as a format to express the provenance of scientific statements. The suggested model is called "nanopublications" and represents a fundamental scientific statement with associated context. Precisely, a nanopublication consists of three named graphs: one on data, one on provenance, and one on publication metadata (Groth, Gibson and Velterop 2010).

However, named graphs have a limit: they do not allow managing the provenance of implicit triples in the presence of update queries. RDFS allows the addition of semantics to RDF triples, so it is possible to derive new implicit triples that are not explicitly declared through inference rules. The moment an update query erases a named graph, all the logic of the triple associates gets lost along with the data, and there is no way to separate the two aspects. *RDF/S graphsets,* and its evolution *RDF triple coloring,* extend named graphs to allow RDFS semantics. A graphset is a set of named graphs. It is associated with a URI, preserving provenance information lost following an update, and registering co-ownership of multiple named graphs (Pediaditis, et al. 2009). Similarly, *RDF triple coloring* allows managing scenarios where the same data has different resources, but co-ownership is implicit (Flouris, et al. 2009). Table 2 shows four quadruples whose fourth element is the "color", the triple source, to understand the problem better.

S	**P**	**O**	**"Color"**
TheWashingtonPost	rdf:type	Newspaper	C_4
Newspaper	rdf:type	rdfs:Class	C_3
Newspaper	rdfs:subClassOf	MassMedia	C_3
MassMedia	rdfs:subClassOf	Media	C_5

Table 3 RDF triple coloring example

From the statements in Table 2, it is possible to infer that *Newspaper* is a subclass of *Media* since *Newspaper* is a subclass of *Massmedia* and *Massmedia* is a subclass of *Media*. Thus the origin of the implicit statement *(Newspaper, rdfs:subClassOf, Massmedia)* is C_3 and C_5. Named graphs could express this double provenance only with two separate quadruples. However, the query "returns the triple colored C_3" would falsely return *(Newspaper, rdfs:subClassOf, Massmedia)*, ignoring that the provenance is not C_3 but C_3 and C_5. *RDF triple coloring* solves the problem by introducing the operator +, such that $C_{3,5} = C_3 + C_5$. $C_{3,5}$ is a new URI assigned to those triples that have as their source both C_3 and C_5.

Both *RDF/S graphsets* and *RDF triple coloring* are serializable in TriG, TriX, and N-Quads, do not need proprietary terms or external vocabularies and are scalable. However, *RDF/S graphsets* do not comply with either the RDF data model or the SPARQL algebra, unlike *RDF triple coloring*, which is fully compatible.

On the other hand, quadruples are not the only strategy to correlate RDF triples with provenance information. Additionally, the RDF data model can be extended to achieve this goal. The first proposal of this kind was Notation 3 Logic, which introduced the *formulae* (Berners-Lee, Notation 3 Logic 2005). *Formulae* allow producing statements on N3 sentences, which are encapsulated by the syntax {...}. Berners-Lee and Connolly also proposed a *patch file format* for RDF deltas, or three new terms, using N3 (Berners-Lee and Connolly, Delta: an ontology for the distribution of differences between RDF graphs 2004):

1. diff:replacement, that allows expressing any change. Deletions can be written as {…} diff:replacement {}, and additions as {} diff:replacement {…}.
2. diff:deletion, which is a shortcut to express deletions as {…} diff:deletion {…}.
3. diff:insertion, which is a shortcut to express additions as {…} diff:insertion {…}.

The main advantage of this representation is its economy: given two graphs G1 and G2, its cost in storage is directly proportional to the difference between the two graphs. Therefore, it is a scalable approach. However, while conforming to the SPARQL algebra, N3 does not comply with the RDF data model and relies on the N3 Logic Vocabulary.

Adopting a completely different perspective, RDF$^+$ solves the problem by attaching a provenance property and its value to each triple, forming a quintuple (Table 4). In addition, it extends SPARQL with the expression "WITH META *Metalist*", which includes graphs specified in *Metalist*, containing RDF$^+$ meta knowledge statements (Dividino, et al. 2009). To date, RDF$^+$ is not compliant with any standard, neither the RDF data model, nor SPARQL, nor any serialization formats.

Subject	**Predicate**	**Object**	**Meta-property**	**Meta-value**
:ra/15519	foaf:name	“Silvio Peroni”	:accordingTo	orcid:0000-0002-8420-0696

Table 4 An RDF$^+$ quintuple

Also, *SPOTL(X)* allows expressing a triple provenance through quintuple (Hoffart, et al. 2013). Indeed, the framework's name means Subject Predicate Object Time Location. Optionally, it is possible to create sextuples that add context to the previous elements. *SPOTL(X)* is concretely implemented in YAGO, a knowledge base automatically built from Wikipedia, given the need to specify which Time, space, and context a specific statement is true. Outside of YAGO, *SPOTL(X)* does not follow either the RDF data model or the SPARQL algebra, and there is no standard serialization format.

Similarly, *annotated RDF* (aRDF) does not currently have any standardization. A triple annotation has the form (s, p: λ, o), where λ is the annotation, always linked to the property (Udrea, Recupero and Subrahmanian 2010). *Annotated RDF Schema* perfects this pattern by annotating an entire triple and presenting a SPARQL extension to query annotations, called AnQL (Zimmermann, et al. 2012). In addition, it specifies three application domains: the temporal, fuzzy, and provenance domains (Table 5).

Domain	**Annotated triple**	**Meaning**
Temporal	(niklasZennstrom, ceoOf, skype): [2003, 2007]	Niklas was CEO of Skype during the period 2003 to 2007
Provenance	(niklasZennstrom, ceoOf, skype): wikipedia	Niklas was CEO of Skype according to Wikipedia
Fuzzy	(skype, ownedBy, bigCompany): 0.3	Skype is owned by a big company to a degree not less than 0.3
Temporal, provenance, and fuzzy	(niklasZennstrom, ceoOf, skype): <[2003, 2007], 1, wikipedia>	Niklas was without doubt CEO of Skype during the period 2003 to 2007, according to Wikipedia

Table 5 Annotated RDF Schema application examples

The most recent proposal in extending the RDF data model to handle provenance information was RDF*, which embeds triples into triples as the subject or object (Hartig and Thompson 2019). Its main goal is to replace *RDF Reification* through less verbose and redundant semantics. Since there is no serialization to represent such syntax, Turtle*, an extension of Turtle to include triples in other triples within << and >>, has also been introduced. Similarly, SPARQL* is an RDF*-aware extension for SPARQL. Later, RDF* was proposed to allow statement-level annotations in RDF streams by extending RSP-QL to RSP-QL* (Keskisärkkä, et al. 2019). YAGO4 has adopted RDF* to attach temporal information to its facts, expressing the temporal scope through *schema:startDate* and *schema:endDate* (Tanon, Weikum and Suchanek, YAGO 4: A Reason-able Knowledge Base 2020). For example, to express that Douglas Adams, *Hitchhiker's Guide to the Galaxy*'s author, lived in Santa Barbara until 2001 when he died, YAGO4 records << *Douglas Adams schema:homeLocation Santa Barbara* >> *schema:endDate 2001*.

After discussing possible RDF extension, two strategies encapsulate provenance in RDF triples: PaCE and singleton properties. Provenance Context Entity (Pace) is an approach concretely implemented in the Biomedical Knowledge Repository (BKR) project at the US National Library of Medicine (Sahoo, Bodenreider, et al. 2010). Its implementation is flexible and varies depending on the application. It allows three granularity levels: the provenance can be linked to the subject, predicate, and object of each triple, only to the subject or only to the subject and predicate, through the property *provenir:derives_from*. Therefore, such a solution depends on the Provenir ontology, and it is not scalable because it causes *triple bloat*. Apart from these two flaws, it has several advantages: it leads to 49% less triple than *RDF Reification*, does not involve blank nodes, is fully compatible with the RDF data model and SPARQL, and allows serialization in any RDF format (RDF/XML, N3, Turtle, N-Triples, RDF-JSON, JSON-LD, RDFa and HTML5 Microdata).

Conversely, singleton properties are inspired by set theory, where a singleton set has a single element. Similarly, a singleton property is defined as "a unique property instance representing a newly established relationship between two existing entities in one particular context" (Nguyen, Bodenreider and Sheth 2014). This goal is achieved by connecting subjects to objects with unique properties that are singleton properties of the generic predicate via the new *singletonPropertyOf* predicate. Then, meta-knowledge can be attached to the singleton property (Table 6). This strategy has been shown to have advantages in terms of query size and query execution time over PaCE (tested on BKR) but disadvantages in terms of triples' number where multiple predications share the same source. Beyond that, singleton properties have the same advantages and disadvantages as PaCE: they rely on a non-standard term, are not scalable, adhere to the RDF data model and SPARQL, and are serializable in any RDF format.

Subject	Predicate	Object
:ra/15519	:name#1	“Silvio Peroni”
:name#1	:singletonPropertyOf	foaf:name
:name#1	:accordingTo	orcid:0000-0002-8420-0696

Table 6 Singleton property and its meta knowledge assertion example

Table 7 summarises all the considerations on the advantages and disadvantages of the listed RDF-based strategies.

Approach	**Tuple type**	**Compliance with the RDF data model**	**Compliance with SPARQL**	**RDF serialiSations**	**External vocabulary**	**Scalable**
Named graphs	Quadruple	+	+	TriG, TriX, N-Quads	-	+
RDF/S graphsets	Quadruple	-	-	TriG, TriX, N-Quads	-	+
RDF triple coloring	Quadruple	+	+	TriG, TriX, N-Quads	-	+
N3Logic	Triple (in N3)	-	+	N3	N3 Logic Vocabulary	+
aRDF	Non-standard	-	-	-	-	+
Annotated RDF Schema	Non-standard	-	-	-	-	+
RDF$^+$	Quintuple	-	-	-	-	+
SPOTL(X)	Quintuple/sextuple	-	-	-	-	Depends on implementation

RDF*	Non-standard	-	-	Turtle* (non-standard)	-	-
PaCE	Triple	+	+	RDF/XML, N3, Turtle, N-Triples, RDF-JSON, JSON-LD, RDFa, HTML5 Microdata	Provenir ontology	-
Singleton property	Triple	+	+	RDF/XML, N3, Turtle, N-Triples, RDF-JSON, JSON-LD, RDFa, HTML5 Microdata	*singletonPropertyOf* property	-

Table 7 Advantages and disadvantages of all metadata representations models to add provenance information to RDF data.

Finally, there are data models alternative to RDF to organize knowledge. The General Semistructured Meta-model (GSMM) is a meta-model to aggregate heterogeneous data models into a single formalism to manage them in a homogeneous way or compare (Damiani, et al. 2019). A triple-based database can be converted to a GSMM graph by introducing nodes for subjects, predicates, and objects, where predicates have an incoming edge labeled < TO >, and an incoming edge labeled < FROM >. Since predicates are modeled as nodes, GSMM supports reification and allows to represent provenance. On the other hand, research exists to convert knowledge bases' entities into embeddings in a vector space (Suchanek, et al. 2019). Unable operations in RDF representations can be performed with embeddings, such as predicting links (using neural networks) or new facts (using logical rules).

4.2.2 KNOWLEDGE ORGANISATION SYSTEMS FOR RDF PROVENANCE

Historically, many vocabularies and ontologies have been introduced to represent provenance information, either upper ontologies, domain ontologies, and provenance-related ontologies. Among the upper ontologies, the Open Provenance Model stands out because of its interoperability. It describes the history of an entity in terms of processes, artifacts, and agents (Moreau, Clifford, et al. 2011), a pattern that will be discussed later about the PROV Data Model (2013). On the other hand, the Proof Markup Language (PML) is an ontology designed to support trust mechanisms between heterogeneous web services (Pinheiro da Silva, McGuinness and Fikes 2006).

About domain-relevant models, there is the Provenir Ontology for eScience (Sahoo and Sheth, Provenir Ontology: Towards a Framework for eScience Provenance Management 2009), PREMIS for archived digital objects, such as files, bitstreams, and aggregations (Caplan 2017), and Semantic Web Applications in Neuromedicine (SWAN) Ontology to model a scientific discourse in the context of biomedical research (Ciccarese, et al. 2008). Finally, the Dublin Core Metadata Terms allows to express the provenance of a resource and specify what is described (e.g., dct:BibliographicResource), who was involved (e.g., dct:Agent), when the changes occurred (e.g., dct:dateAccepted), and the derivation (e.g., dct:references), sometimes very precisely (DCMI Metadata Terms 2020).

All the requirements and ontologies mentioned have been merged into a single data model, the PROV Data Model (Moreau, Clifford, et al. 2011), translated into the PROV Ontology using the OWL 2 Web Ontology Language (PROV-O: The PROV Ontology 2013). It provides several classes, properties, and restrictions, representing provenance information in different systems and contexts. Its level of genericity is such that it is even possible to create new classes and data model-compatible properties for new applications and domains. Just like the Open Provenance Model, PROV-DM captures the provenance under three complementary perspectives:

- *Agent-centered provenance* entails people, organizations, software, inanimate objects, or other entities involved in generating, manipulating, or influencing a resource. For example, it is possible to distinguish between the author, the editor, and the publisher concerning a journal article. PROV-O maps the responsible agent with prov:Agent, the relationship between an activity and the agent with prov:wasAssociatedWith, and an entity’s attribution to an agent with prov:wasAttributedTo.
- *Object-centred-provenance*, which is the origin of a document’s portion from other documents. Taking the example of the article, a fragment of it can quote an external document.

PROV-O maps a resource with prov:Entity, whether physical, digital, or conceptual, while the predicate prov:wasDerivedFrom expresses a derivation relationship.

- *Process-centered provenance*, or the actions and processes necessary to generate a resource. For example, an editor can edit an article to correct spelling errors using the previous version of the document. PROV-O expresses the concept of action with prov:Activity, the creation of an entity with the predicate prov:wasGeneratedBy, and the use of another entity to complete a passage with prov:used.

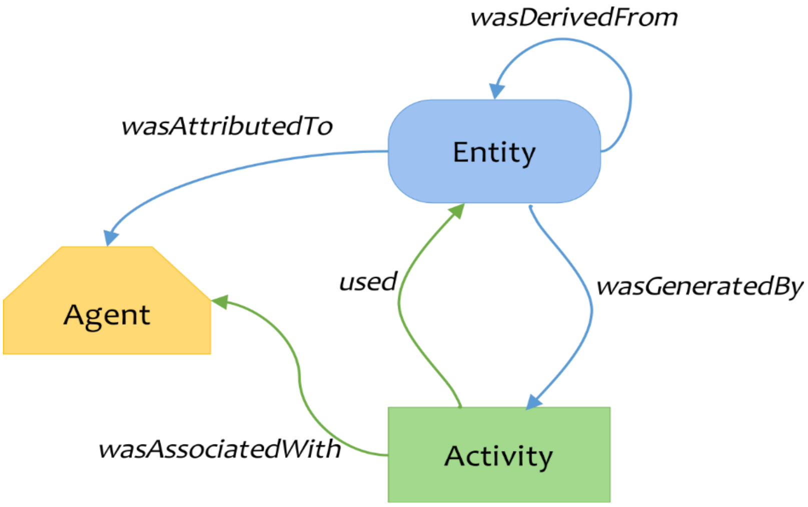


Figure 3 High level overview diagram of PROV records (PROV Model Primer 2013)

The diagram in Figure 1 provides a high-level view of the discussed concepts' structure, constituting the so-called "starting point terms". PROV-O is more extensive and provides modularly sophisticated entities, agents, activities, and relationships, namely "expanded terms" and "qualified terms".

The OpenCitations Data Model, used in this research, relies on the flexibility of PROV-O to record the provenance of bibliographic datasets (Daquino, Peroni, et al., The OpenCitations Data Model 2020). Each bibliographical entity described by the OCDM is annotated with one or more snapshots of provenance. The snapshots are of type prov:Entity and are connected to the bibliographic entity described through prov:specializationOf, predicate present in the mentioned "expanded terms". Being the specialization of another entity means sharing every aspect of the latter and, in addition, presenting more specific aspects, such as an abstraction, a context, or, in this case, a time. In addition, each snapshot records the validity dates (prov:generatedAtTime, prov:invalidatedAtTime), the agents responsible for both creation and modification of the metadata (prov:wasAttributedTo), the primary sources (prov:hadPrimarySource) and a link to the previous snapshot in time (prov:wasDerivedFrom). The model is summarised in Figure 2.

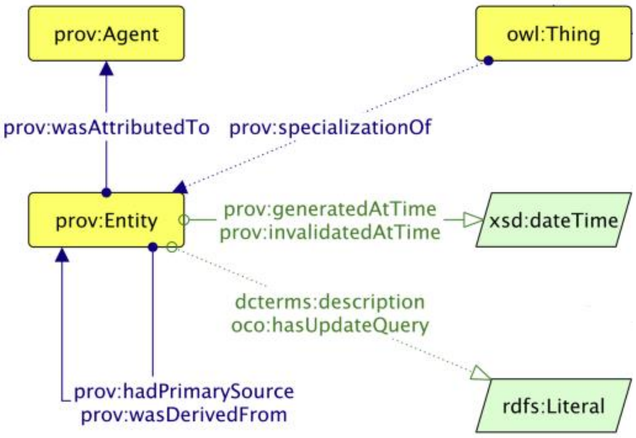


Figure 4 Provenance in the OpenCitations Data Model

In addition, OCDM extends the Provenance Ontology by introducing a new property called *hasUpdateQuery*, a mechanism to record additions and deletions from an RDF graph with a SPARQL INSERT and SPARQL DELETE query string. The *snapshot-oriented* structure, combined with a system to explicitly indicate how a previous snapshot was modified to reach the current state, makes it easier to recover the current statements of an entity and restore an entity to a specific snapshot. The current statements are those available in the present dataset, while recovering a snapshot s_i means applying the reverse operations of all update queries from s_n to s_{i+1} (Peroni, Shotton and Vitali 2016).

Initially adopted for the OpenCitations Corpus, this expedient was designed to foster reusability in other contexts and is the added value of the provenance model proposed in the OCDM, which is the basis for the library to perform time agnostic queries presented in this work.

The existing literature on tracking changes in RDF data will be deepened in the next section, focusing on the sources that inspired the OpenCitations provenance model.

4.3 TRACKING CHANGES OF RDF DATA

In section 4.2, several strategies have been introduced to correlate RDF data with provenance information. Up to now, the discourse has been generic and extended to all the “content” category dimensions summarized in Table 1, that is, to all the possible provenance types: the attribution, the processes, the justification, the entailment, and the versioning. The Time Agnostic Library, which is the main contribution of this work, deals with versioning and the temporal dimension of provenance.

However, even Time is a multidimensional concept, which can be evaluated from two points of view. On the one hand, the *transaction time*, defined in the temporal databases literature as “the time a fact was present in a database as stored data”. On the other, the *valid Time*, which is instead “the time a fact was true in reality” (Snodgrass 1986). For example, the statement (*dbr:Rome*, *dbo:capital*, *dbr:Roman_Empire*) is currently found in DBPedia[1]. Nevertheless, in the present, that is a false statement because its valid Time goes from 27 B.C. to 395 A.D. when the Empire split into the Western Roman Empire and the Eastern Roman Empire and the Western capital was moved to Milan. “Validity” is a dense concept, especially in Digital Humanities, subject to conjectures that transcend the boundaries of the current discourse (Barabucci, Tomasi and Vitali 2021). Instead, we will focus exclusively on transaction time and, in particular, on keeping track of the changes in RDF datasets.

Before discussing how RDF datasets currently track changes, the importance of implementing such policies must be understood. The Web of Data has an intrinsic dynamic nature, and the Dynamic Linked Data Observatory was born to measure how it evolves. The project was launched in 2012 with the aim of releasing weekly snapshots of the Semantic Web based on 791 domains[2] (Umbrich, et al. 2010). In 2013, the project monitored the evolution of 86,696 RDF documents for 29 weeks (Käfer, et al. 2013). Among the most significant conclusions, it was found that 37.8% of documents were modified during that period, about 20% of the documents were temporarily unavailable, and 5% disappeared permanently. Without a system to understand when a resource was altered, why it was updated, and who was responsible for its revision, the information’s reliability is seriously questioned.

[1] https://dbpedia.org/page/Rome

[2] http://km.aifb.kit.edu/projects/dyldo/data/

4.3.1 STORING AND QUERYING DYNAMIC LINKED OPEN DATA

In order to store and query how an RDF dataset evolves, various archiving policies have been elaborated, namely *independent copies*, *change-based* and *timestamp-based* policies (Fernández, Polleres and Umbrich 2015). Table 8 lists the main knowledge bases, version control systems, and archives for RDF, divided by storage policy. They will be deepened in the following paragraphs, and the allowed query typologies will be discussed.

Archiving policy	**Datasets / Software**
Independent copies (IC)	DBPedia, Wikidata, YAGO, Dynamic Linked Data Observatory, SemVersion, PromptDiff
Change-based (CB)	(Im, Lee and Kim 2012), (Papavasileiou, et al. 2013), R&Wbase
Timestamp-based (TB)	x-RDF-3X, v-RDFCSA
Hybrid	OSTRICH (CB/TB), OpenCitations Corpus (CB/TB), (Tanon and Suchanek 2019) (IC/CB/TB)

Table 8 Datasets and software divided by storage policy.

Two query and focus types are identified in (Fernández, Umbrich, et al. 2016). On the one hand, a query can be materialized or structured; on the other, the focus can affect a version or a delta. Combining query and focus types results in six possible retrieval functionalities (Table 9). 1) Version materialization: the request to obtain a full version of a specific resource. This feature is the most common, provided by any version control system for RDF. 2-3) Single-version structured query and cross-version structured query: queries made on a specific version or through different versions. The latter is also called a time-traversal query. 4) Delta materialization is to get the differences between two versions of a specific resource. This feature is handy for RDF authoring applications and operations in version control systems, such as merge or conflict resolution. 5-6) Single-delta structured and cross-delta structured queries: the equivalent of 2-3), but satisfied with deltas instead of versions.

	Materialization	**Structured queries**	
		Single Time	**Cross time**
Version	Version materialization *Get snapshot at Time t_i*	Single-version structured queries *Articles written by a specific author at time t_i*	Cross-version structured queries *Articles associated with the same DOI simultaneously*
Delta	Delta materialization *Get delta at Time t_i*	Single-delta structured queries *DOI modified between two consecutive snapshots*	Cross-delta structured queries *The most significant change in the number of articles in the history of the dataset*

Table 9 Retrieval functionalities according to (Fernández, Umbrich, et al. 2016).

The policy called *independent copies* consists of storing each version separately. Two levels of granularity are possible: either a copy of the entire dataset is saved, or only resources that change. This strategy is sometimes defined as *physical snapshots* in the literature (Peroni, Shotton and Vitali 2016). It is the most straightforward model to implement and allows obtaining versions materializations with great ease. However, the disadvantages are much more consistent: first, a massive amount of space and Time is needed; furthermore, given the different statements' versions, further diff mechanisms are needed to identify what has changed. Nevertheless, to date, this is the archiving policy adopted by most systems and knowledge bases.

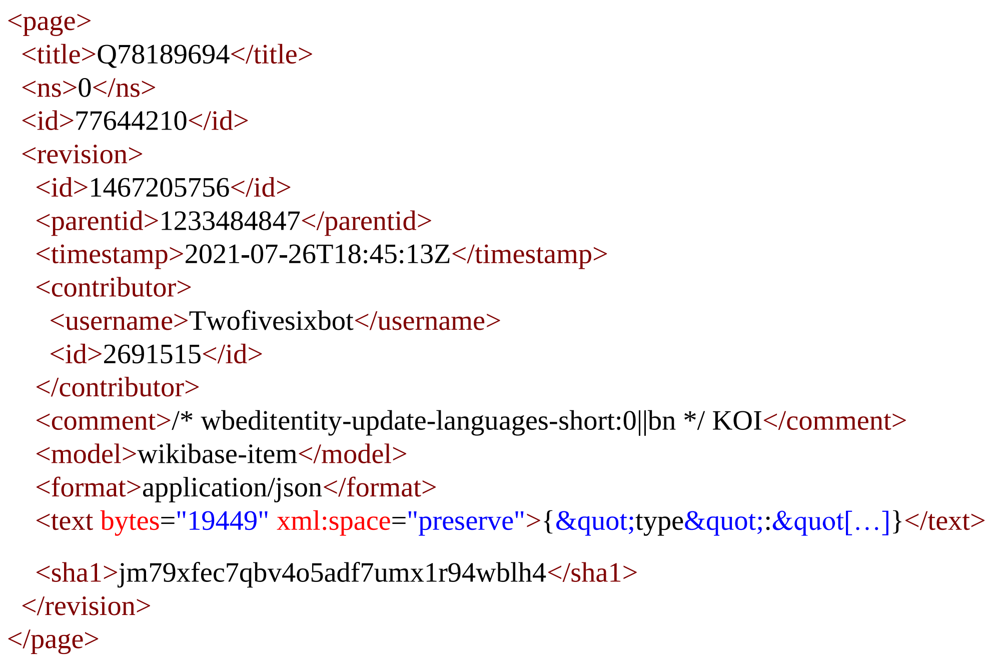
The first version control systems for RDF were PromptDiff (Noy and Musen 2002) and SemVersion (Völkel, et al. 2005), specially tailored for ontologies. Inspired by CVS, the classic version control system for text documents, they save each version of an ontology in a separate space. In addition, PromptDiff provides diff algorithms to compute deltas between two versions and see what has changed, applying ten heuristic matchers. The results of a matcher become the input for others until they produce no more changes. On the other hand, SemVersion provides two diff algorithms: one *structure-based*, which returns the difference between explicit triples in two graphs, the other *semantic-aware*, which also considers the triples inferred through RDFS relations. Differences are calculated on the fly in both approaches, while all ontology's versions take up space on the disk. For this reason, SemVersion and PromptDiff are classified as having *independent-copies* archiving policies, despite the article from which this classification is taken consider them as *changed-based* systems (Fernández, Polleres and Umbrich, Towards Efficient Archiving of Dynamic Linked 2015). As for the allowed queries, they are limited to the delta end version materialization in both cases.

Concerning knowledge bases, DBpedia (Lehmann, et al. 2015) publicly releases snapshots of the entire dataset at regular intervals. Therefore, in the specific case of DBpedia, a further problem arises: many changes may not be reflected in the snapshots, that is, all statements with a lifespan shorter than the interval between snapshots. There are proposals to fill this gap, such as exploiting Wikipedia's revisions history information (Orlandi and Passant 2011). Similarly, Yago releases backups of the whole dataset, downloadable in the Downloads section of the website[3]. Since the Yago data model has changed significantly from the first to the fourth edition, each can be downloaded separately.

On the other hand, Wikidata does not save the whole dataset but only the resources that change (F. Erxleben, et al. 2014). Wikibase, the database used for Wikidata, creates a revision associated with a specific entity every Time the related page is modified (Dooley and Božić 2019). Within each revision, in the "text" field, there is a complete copy of that page after the change. Some metadata are also saved, such as the timestamp, the contributor's username and id, and a comment summarizing the modifications (Figure 5). This information is stored in compressed XML files and made available for download on the Wikidata website[4]. However, the content of the text field is not in XML format, but in JSON format, with all non-ASCII characters escaped. On the Wikidata site, it is possible to explore the content of a single revision and compute the delta between two or more versions on the fly through the user interface. Though, there is no way to perform SPARQL queries on revisions.

[3] https://yago-knowledge.org/downloads

[4] https://www.wikidata.org/wiki/Wikidata:Database_download



```
<page>
  <title>Q78189694</title>
  <ns>0</ns>
  <id>77644210</id>
  <revision>
    <id>1467205756</id>
    <parentid>1233484847</parentid>
    <timestamp>2021-07-26T18:45:13Z</timestamp>
    <contributor>
      <username>Twofivesixbot</username>
      <id>2691515</id>
    </contributor>
    <comment>/* wbeditentity-update-languages-short:0||bn */ KOI</comment>
    <model>wikibase-item</model>
    <format>application/json</format>
    <text bytes="19449" xml:space="preserve">{&quot;type&quot;:&quot[…]}</text>

    <sha1>jm79xfec7qbv4o5adf7umx1r94wblh4</sha1>
  </revision>
</page>
```

Figure 5 Wikidata revision example

The *change-based* policy was introduced to solve scalability problems caused by the *independent copies* approach. It consists of saving only the deltas between one version and the other. For this reason, delta materialization is costless. On the flip side, to support version-focused queries, additional computational costs for delta propagation are required.

The first proposal was described in *A Version Management Framework for RDF Triple Stores* (Im, Lee and Kim 2012). The idea is to store the original dataset and the deltas between two consecutive versions. However, as has been said, performing version queries requires rebuilding that state on the fly. In order to avoid performance problems, deltas are compressed in Aggregated Deltas to directly compute the version of interest instead of considering the whole sequence of deltas. In other words, all possible deltas are stored in advance, and duplicated or unnecessary modifications are deleted. Finally, the article analyzes the performance for structured queries on a single version, on a single delta, and cross-delta. However, no mention is made of possible queries on multiple versions.

If the dataset’s data model includes RDFS, reducing the deltas' size or generating high-level deltas is possible. The article *High-Level Change Detection in RDF(S) KBs* introduces the *language of change*, where every possible change has well-defined semantics (Papavasileiou, et al. 2013). In particular, it proposes 132 types of change, 54 of which are basic, 51 are composite, and 27 are heuristic changes. Deltas are computed on the fly from added and removed triples – that is, from low-level deltas – and are both human-readable and machine-interpretable. See Table 7 for an example of a heuristic change.

Low-Level Delta		High-Level Delta
Added Triples	Deleted Triples	Detected Changes
(Stuff,subClassOf, Persistent)	(Stuff,subClassOf, Existing)	Rename Class(Existing, Persistent)
(started on,domain, Persistent)	(started on,domain, Existing)	
(Persistent,type,class)	(Existing,type,class)	

Table 10 High-level changes compared to low-level changes.

However, low-level deltas are easier to compute and manage, although they take up more disk space and are less expressive. Moreover, it is impossible to generate high-level deltas without underlying semantics based on RDFS and OWL. Therefore, such a solution can not be implemented in any context. Finally, the article makes no mention of possible structured queries.

A concrete example of a *change-based* policy application is R&Wbase, a version control system inspired by Git but designed for RDF (Sande, et al. 2013). Triples are stored in quads, where the context identifies the version and whether the triple was added or removed. More specifically, each delta is associated with a version number higher than all previous values. Additions have an even value of 2y, while deletions have an odd value of 2y+1. Finally, insertions-related graphs store metadata, such as the date, the responsible agent, and the parent delta. The main advantage of this approach is that it allows single-version structured queries at query-time: a so-called interpretation layer is responsible for translating SPARQL queries to find all the ancestors of a resource at a specific time. In other words, to answer a query on a $2y_n$ version, the interpreter finds all ancestors $A_{2yn} = \{2_{yi},...,2_{yj}\}$. The query specifies the Time via FROM <version_graph_URI>, where the graph's path is either a hash or "master". In order to speed up the process, triples in both the additions and deletions graphs are excluded, and the most frequent queries can be cached. The article does not mention any other query type and whether it can indicate more than one graph for cross-version structured queries. In any case, since a not human-readable version's URI must be known, that could be considered as a cumbersome solution.

On the other hand, the *timestamp-based* policy annotates each triple with the version's timestamp in which that statement was in the dataset. Annotated RDF Schema can be used to achieve this, combined with AnQL to perform queries, as seen in chapter 4.2.1 (Zimmermann, et al. 2012). However, implementations of that solution are not known. On the contrary, x-RDF-3X is a database for RDF designed to manage high-frequency online updates, versioning, time-travel queries, and transactions (Neumann and Weikum 2010). The triples are never deleted but are annotated with two fields: the insertion and deletion timestamp, where the last one has zero value for currently living versions. Afterward, updates are saved in a separate workspace and merged into various indexes at occasional savepoints. A dictionary encodes strings in short IDs, and compressed clustered B+ trees are exploited to index data in lexicographic order. Because of indexes, time-travel queries are speedy, but no approach to return deltas or query them is mentioned.

v-RDFCSA uses a similar strategy but excels in reducing space requirements, managing to compress 325 GB of storage into 5.7 - 7.3GB (Cerdeira-Pena, et al. 2016). To achieve that result, it compresses both the RDF archive and the timestamps attached to the triples. All types of queries are explicitly allowed.

Finally, there are hybrid storage policies that combine the changed-based approach with the timestamp-based approach. For example, OSTRICH is a triplestore that retains the first version of a dataset and subsequent deltas, as seen in (Im, Lee and Kim 2012). However, it merges changesets based on timestamps to reduce redundancies between versions, adopting a change-based and timestamp-based approach simultaneously (Taelman, Sande and Verborgh 2018). OSTRICH supports version materialization, delta materialization, and single-version queries.

The OpenCitations Corpus embraces a similar hybrid approach, mirror-like and opposite to that seen in (Im, Lee and Kim 2012) and OSTRICH: the present state is the only one stored, not the original one. For each entity, a provenance graph is generated as a result of an update. The delta versus the next version is expressed as a SPARQL query in the property *oco:hasUpdateQuery*. In addition, each provenance graph contains transactional time information, expressed via *prov:generatedAtTime* and *prov:invalidatedAtTime*, that is, the insertion and deletion timestamps. The advantage is that the most interesting dataset's state, the current one, is immediately available and must not be reconstructed. It is worth mentioning that, to date, the OpenCitations Corpus is the only bibliographical database to implement change-tracking mechanisms. Among the leading players in the field, neither Web of Science nor Scopus have adopted solutions in this regard.

To conclude, software exists that adopts all three archiving policies. For example, (Tanon and Suchanek 2019) propose a system to fill the already mentioned Wikidata gap, which provides provenance data but does not allow queries. XML dumps downloaded from Wikidata are organized into four graphs: a global state graph, which contains a named graph on the global state of Wikidata after each revision; an addition and deletion graphs, which contain all the added and deleted triples for revision; and a default graph, containing metadata for each revision, such as the author, the timestamp, the id of the modified entity, the previous version of the same entity and the URIs of the additions, deletions, and global state graphs. Since the sum of these graphs would weigh exabytes, they are not directly saved into a triplestore, but RocksDB[5] is used to store specific indexes. Four kinds of indexes are generated: dictionary indexes, in which each string is associated to an integer and vice versa; content indexes, which associate the permutations *spo*, *pos*, and *osp* to the respective transaction time in the form [start, end[; revision indexes, which provides the set of added and removed triples for a given revision; and meta indexes, which provide the relevant metadata for each revision. The use of each storage policy allows managing all kinds of queries efficiently.

Table 11 summarizes all the considerations regarding possible query categories for various software and whether these are computed on the fly or need an index. Knowledge bases and datasets, such as Dbpedia, Yago, Wikidata, and the OpenCitations Corpus, were excluded from the table since they are interesting only for storage policies and separate software is required for queries. For the same reason, the proposal by Papavasileiou *et al.* is not categorized either (Papavasileiou, et al. 2013).

Software	**Version materialization**	**Delta materialization**	**Single-version structured query**	**Cross-version structured query**	**Single-delta structured query**	**Cross-delta structured query**	**On the fly**
PromptDiff	+	+	-	-	-	-	+
SemVersion	+	+	-	-	-	-	+
(Im, Lee and Kim 2012)	+	+	+	-	+	+	-
R&Wbase	+	+	+	-	-	-	+
x-RDF-3X	+	-	+	+	-	-	-

[5] https://rocksdb.org/

v-RDFCSA	+	+	+	+	+	+	-
OSTRICH	+	+	+	-	-	-	-
(Tanon and Suchanek 2019)	+	+	+	+	+	+	-

Table 11 Software cataloged by allowed query types and the need for indexing.

From Table 11, it is clear that all the existing solutions need indexes and pre-processing to manage time-travel queries efficiently. Software that performs operations on the fly, such as R&Wbase, does not allow cross-version structured queries. This flaw can prove fatal in dynamic open linked datasets that constantly receive many updates, such as Wikidata. This work aims to introduce a Python library to perform time-agnostic queries on the fly, exploiting the OpenCitations’ provenance model.

5 MATERIALS AND METHODS

As discussed in 4, Semantic Web technologies (RDF, OWL, SPARQL) did not initially allow recording or querying change-tracking provenance. For this reason, it is necessary to adopt an external provenance model. In the context of this work, the model adopted is that of OpenCitations, as described in 4.2.2. Although this annotation system has been designed for bibliographic and citation data, it is generic and can be used in any environment. Therefore, the Python library that is being introduced is also generic and working with any RDF dataset that documents provenance as OpenCitations does. Its purpose is to perform time-agnostic queries, which are carried out not only on the dataset's current state but on its whole history. The taxonomy by (Fernández, Polleres and Umbrich 2015), already introduced in 4.3.1, will be used to illustrate which methodologies have been adopted to achieve this goal. Therefore, a distinction will be made between version and delta materializations, single and cross-version structured queries, single and cross-delta structured queries.

5.1 VERSION AND DELTA MATERIALIZATION

Obtaining a version materialization means returning an entity state at a given period. Thus, the starting information is a resource URI and a time, which can be instant or an interval. Then, it is necessary to obtain the provenance information available for that entity, querying the dataset on which it is present. In particular, the crucial data regards the existing snapshots, their generation time, and update queries expressing changes through SPARQL strings. The OpenCitations Data Model links entities to snapshots via prov:specializationOf and conveys the mentioned properties via prov:wasGeneratedAtTime and oco:hasUpdateQuery. If there are no snapshots for a given entity, it is impossible to reconstruct its past version, so the algorithm ends. On the other end, if the change-tracking provenance does exist, further processing is required. From a performance point of view, the main problem is how to get the status of a resource in a given time without reconstructing the whole history, but only the portion needed to get the result. Suppose t_n is the present state and having all the SPARQL update queries. The status of an entity at the time t_{n-k} can be obtained by adding the inverse queries in the correct order from n to n-k and applying the queries sum to the entity's present graph.

For example, consider the graph of the entity <https://example/id/1>. At present, this identifier has a literal value of “10.5281/zenodo.5172996”. We want to determine if this value has been modified recently, reconstructing the entity at time t_{n-1}. The string associated with the property oco:hasUpdateQuery at time t_n is shown in Figure 6.

```
INSERT DATA {
  GRAPH <https://example/id/> {
        <https://example/id/1>
        <http://www.essepuntato.it/2010/06/literalreification/hasLiteralValue>
        "10.5281/zenodo.5172996".
  }
};
DELETE DATA {
  GRAPH <https://example/id/> {
        <https://example/id/1>
        <http://www.essepuntato.it/2010/06/literalreification/hasLiteralValue>
        “10.5281/zenodo.5151263".
  }
```

Figure 6 SPARQL update query describing how <https://example/id/1> changed at time t_n.

Therefore, to reconstruct which was the literal value of <id/1> at time t_{n-1}, it is sufficient to apply the same update query to the current graph by replacing "DELETE" to "INSERT" and "INSERT" to "DELETE". What was deleted must be inserted, and what was inserted must be deleted to rewind the resource's time. It turns out that <id/1> had a different literal value at time t_{n-1}, namely "10.5281/zenodo.5151263". If the time of interest had been t_{n-2}, it would have been necessary to carry out the same operation with the sum of the update queries associated with t_n and t_{n-1} in this order.

In addition to data, metadata related to a given change can be derived, asking for additional information to the provenance dataset, such as the responsible agent and the primary source. In this way, it is possible to understand who made a specific change and the information’s origin. The OpenCitations Data Model expresses these two properties with prov:wasAttributedTo and prov:hadPrimarySource. Finally, hooks to metadata related to non-reconstructed states can be returned to find out what other snapshots exist and possibly rebuild them.

The flowchart in figure 7 summarizes the version materialization algorithm.

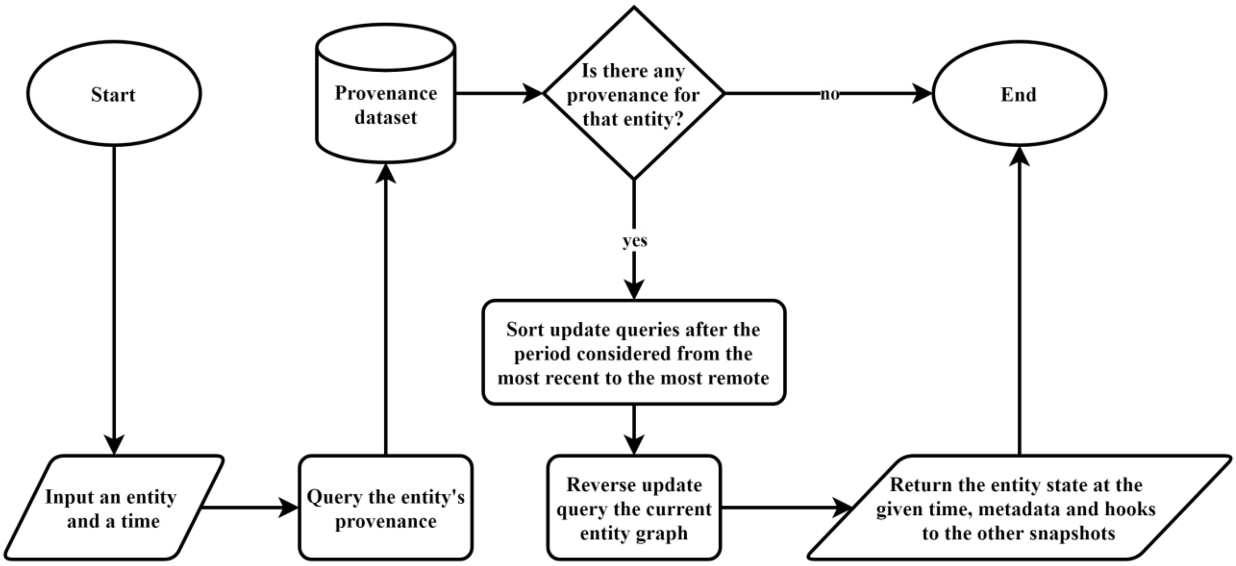

Start
Provenance dataset
Is there any provenance for that entity?
no
End
yes
Sort update queries after the period considered from the most recent to the most remote
Input an entity and a time
Query the entity's provenance
Reverse update query the current entity graph
Return the entity state at the given time, metadata and hooks to the other snapshots

Figure 7 Flowchart illustrating the algorithm to materialize an entity version at a given period.

The process described so far is efficient in materializing a specific entity's version. However, if the goal is to obtain the history of a given resource, adopting the algorithm of Figure 7 would mean executing, for each snapshot, all the update queries of subsequent snapshots, repeating the same update query over and over again. Since every resource graph needs to be output, it is more convenient to run the reverse update query related to each snapshot on the following snapshot graph, which has been previously computed and stored.

On the other hand, obtaining the materialization of a delta means returning the change between two versions. The library does not implement any method to achieve this because it is not needed. The OpenCitations Data Model requires deltas to be explicitly stored as SPARQL update queries strings by adopting a change-based policy. Therefore, the diff is the starting point and is immediately available, without processing to derive it. However, if more than a mere delta is required, and there is the demand to perform a single or cross-delta structured query, it is helpful to have accelerators to accomplish this, illustrated in section 5.2.

5.2 SINGLE-DELTA AND CROSS-DELTA STRUCTURED QUERY

Performing a structured query on deltas means focusing on change instead of the overall status of a resource. If the interest is limited to a specific time interval, it is called a single-delta structured query. On the other hand, if the structured query is carried out on the whole dataset's changes history, it is named a cross-delta structured query. Although the library's purpose is not to offer a version control system, understanding which resources have changed in advance can help narrow the field and achieve faster queries on versions.

Theoretically, employing the OpenCitations Data Model, it is possible to conduct searches on deltas without needing a dedicated library. For example, to find all those identifiers whose string has never been modified, the query in Figure 8 can be used. However, a similar SPARQL string requires the user to have a deep knowledge of the data model. Therefore, it is valuable to introduce a method to simplify and generalize the operation, obscuring the complexity of the underlying provenance pattern.

```
PREFIX datacite: <http://purl.org/spar/datacite/>
PREFIX oco: <https://w3id.org/oc/ontology/>
PREFIX prov: <http://www.w3.org/ns/prov#>
SELECT DISTINCT ?id
WHERE {
   ?se prov:specializationOf ?id;
            oco:hasUpdateQuery ?updateQuery.
   ?id a datacite:Identifier.
   FILTER CONTAINS (
            ?updateQuery, "http://www.essepuntato.it/2010/06/literalreification/hasLiteralValue"
   )
}
```

Figure 8 Example of a direct delta query.

From Figure 8, it is possible to derive two requirements: the user shall identify the entities he is interested in through a SPARQL query and specify the properties to study the change. In addition, to allow both single-delta and cross-delta structured queries, it is necessary to provide for the possibility of entering a time. Consequently, the first step is to find the entities that respond to the user’s query. Secondly, suppose a set of properties has been input. In that case, the previously collected resources must be filtered according to those who have changed those values, which can be obtained from the provenance dataset. On the contrary, if no predicate has been indicated, it is necessary to restrict the field to those entities that have received any modification. Afterward, the results should be filtered according to the specified time if a period was input. Finally, the relevant modified entities are returned concerning the specified query, properties, and time, when they have changed and how.

The flowchart in Figure 9 summarizes the single-delta and cross-delta structured query algorithm.

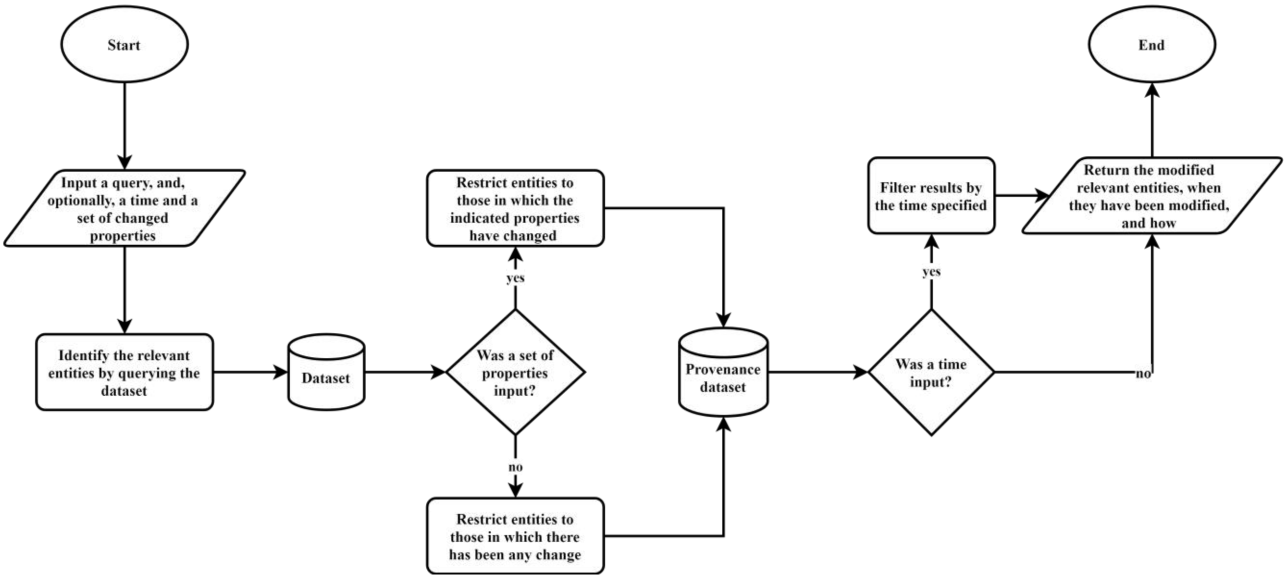

Start
Input a query, and, optionally, a time and a set of changed properties
Identify the relevant entities by querying the dataset
Dataset
Was a set of properties input?
yes
Restrict entities to those in which the indicated properties have changed
no
Restrict entities to those in which there has been any change
Provenance dataset
Was a time input?
yes
Filter results by the time specified
no
Return the modified relevant entities, when they have been modified, and how
End

Figure 9 Flowchart illustrating the algorithm to perform single-time and cross-time structured queries on deltas.

5.3 SINGLE-VERSION AND CROSS-VERSION STRUCTURED QUERY

Running a structured query on versions means resolving a SPARQL query on a specific entity's snapshot if it is a single-version query or on all the dataset's versions in case of a cross-version query. In both cases, a strategy must be devised to achieve the result in a performing manner. According to the OpenCitations Data Model, only deltas are stored; therefore, the dataset's past conditions must be reconstructed to query those states. However, restoring as many versions as snapshots would generate massive amounts of data, consuming time and storage. The adopted solution has been to reconstruct only the past resources significant for the user's query.

Hence, given a query, the goal is to explicit all the variables, materialize every version of each entity found, and align the respective graphs temporally to execute the original query on each. The first step is to process the SPARQL string and extract the triples. The higher the number of URIs, the faster the procedure. Suppose no URI is present, not even as a predicate. In that event, the algorithm is terminated because solving it would mean restoring all the dataset resources' snapshots. If at least one URI is present, each identified triple may be isolated or not. A triple is not isolated if a path exists between its subject variable and a subject URI in the query. In such a case, it is possible to solve the variable using a previously reconstructed entity graph. Consider the example in Figure 10.

```
PREFIX literal: <http://www.essepuntato.it/2010/06/literalreification/>
PREFIX cito: <http://purl.org/spar/cito/>
PREFIX datacite: <http://purl.org/spar/datacite/>
SELECT DISTINCT ?br ?id ?value
WHERE {
   <https://example/br/1> cito:cites ?br.
   ?br datacite:hasIdentifier ?id.
   ?id literal:hasLiteralValue ?value.
}
```

Figure 10 Example of an agnostic query of non-isolated triples.

Once all versions of <br/1> have been materialized, every possible value of the variable ?br is known. At that point, all the possible values that ?id had can be derived from all the URIs of ?br. Also, the variable ?value can be resolved similarly. It is interesting to note that a variable can take different values at different times and at the same time. The bibliographical resource <br/1> probably cites more than just another bibliographical resource. Hence, ?br takes multiple values in all of its snapshots, determining the same for ?id and ?value.

On the other hand, the query is more general if there are isolated triples, and identifying the relevant entities is more demanding. However, if there is at least one URI, it is still possible to narrow the field so that only the strictly necessary entities are restored and not the whole dataset. Since deltas are saved as SPARQL strings, a textual search on all available deltas can be executed to find those containing the known URIs. The difference between a delta triple including all the isolated triple URIs and the isolated triple itself is equal to the relevant entities to rebuild. Figura 11 shows a time-travel query containing an isolated triple, in which only the predicate is known.

```
PREFIX pro: <http://purl.org/spar/pro/>
SELECT DISTINCT ?s ?o
WHERE {
   ?s pro:isHeldBy ?o.
}
```

Figura 11 Agnosting query including an isolated triple.

Identifying all the possible values of ?s and ?o at any time means discovering which nodes have ever been connected by the predicate pro:isHeldBy. This information is enclosed in the values of oco:hasUpdateQuery within the provenance snapshots. First, the update queries containing the predicate pro:isHeldBy must be isolated. Then, they have to be parsed in order to process the triples inside. All subjects and objects linked by pro:isHeldBy are reconstructed to answer the user’s time agnostic query.

It is worth mentioning that a user query can contain both triples isolated and not. In that case, the disconnected triples are processed by carrying out textual searches on the diffs. In contrast, the connected ones are solved by recursively explicating the variables inside them, as we have seen.

After detecting the relevant resources concerning the user’s query, the next step depends on whether it is a single-version or a cross-version query. In the first case, for better efficiency, it is not necessary to reconstruct the whole history of every entity, but only the portion included in the input time. On the contrary, for cross-version queries, all versions of each resource must be restored. In both cases, the method adopted is the version materialization described in 5.1.

However, even after all the relevant data records have been obtained, the initial search cannot be answered. Restored snapshots must be aligned to get a complete picture of events. In particular, since the property oco:hasUpdateQuery only records changes, if an entity has been modified at time t_n, but not at t_{n+1}, that entity will appear in the t_n-related delta but not in the t_{n+1} one. The t_{n+1} graph would not include that resource, although it should be present. As a solution, entities present at time t_n but absent in the following snapshot must be copied to the t_{n+1}-related graph because they have not been modified. Finally, entities’ graphs are merged based on snapshots so that contemporary information is part of the same graph.

After the pre-processing described so far, performing the time-travel query becomes a trivial task. It is sufficient to execute it on all reconstructed graphs, each associated with a snapshot relevant to that query and containing the strictly necessary information to satisfy the user’s request.

The flowchart in Figure 12 summarizes the single-version and cross-version query algorithm.

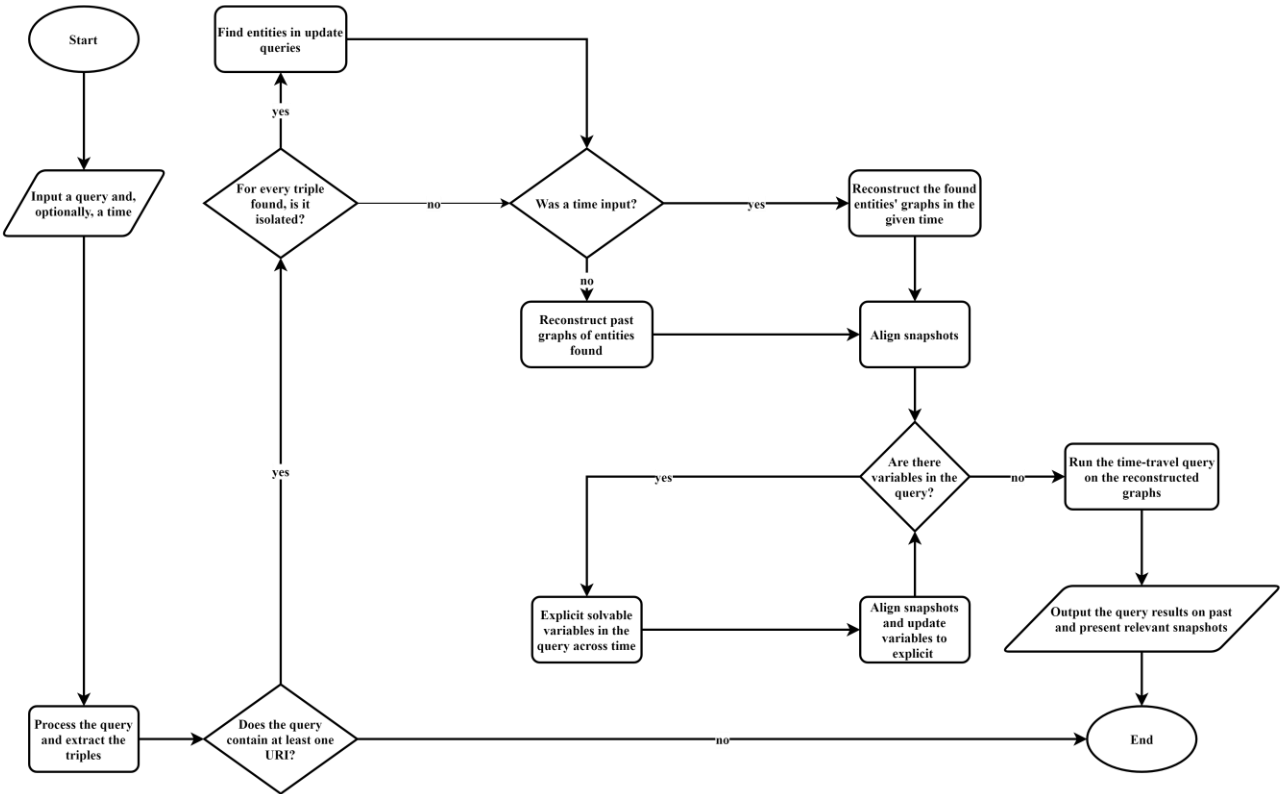

Start
Input a query and, optionally, a time
Process the query and extract the triples
Does the query contain at least one URI?
no
End
yes
For every triple found, is it isolated?
yes
Find entities in update queries
no
Was a time input?
yes
Reconstruct the found entities' graphs in the given time
no
Reconstruct past graphs of entities found
Align snapshots
Are there variables in the query?
yes
Explicit solvable variables in the query across time
Align snapshots and update variables to explicit
no
Run the time-travel query on the reconstructed graphs
Output the query results on past and present relevant snapshots

Figure 12 Flowchart illustrating the algorithm to perform single-time and cross-time structured queries on versions.

6 THE TIME AGNOSTIC LIBRARY

Time-agnostic-library is a Python ≥ 3.7 library that allows performing time-travel queries on RDF datasets compliant with the OCDM v2.0.1 provenance specification (Daquino, Peroni and Shotton 2018). It is available as a package and can be installed with pip via a terminal command.

```
pip install time-agnostic-library
```

This chapter is a high-level description of the Time Agnostic library, helpful to understand its structure and operation. First, the modules are introduced, along with viable configuration parameters. Then, the user-oriented methods are described.

The Time Agnostic library is composed of five modules:

- agnostic_entity, where the AgnosticEntity class is defined, that is the resource to materialize one or all versions based on the available provenance snapshots;
- agnostic_query, where the AgnosticQuery class is introduced, which represents a generic time-travel query. VersionQuery and DeltaQuery inherit from it to perform searches on versions and deltas. Finally, BlazegraphQuery inherits from VersionQuery and allows speeding up some query types, in case Blazegraph is used as a triplestore (Figure 13).

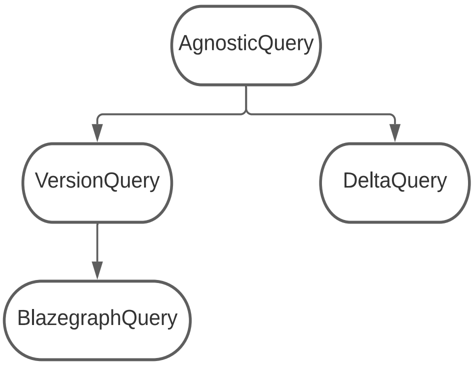


Figure 13 Class hierarchy for time-travel queries.

- prov_entity. The ProvEntity class defines all the change-tracking properties according to the OpenCitations Data Model. Since the class is at the base of all the others, it is reported in full in Figure 14;

```python
from typing import ClassVar
from rdflib import Namespace, URIRef

class ProvEntity:
    PROV: ClassVar[Namespace] = Namespace("http://www.w3.org/ns/prov#")
    DCTERMS: ClassVar[Namespace] = Namespace("http://purl.org/dc/terms/")
    OCO: ClassVar[Namespace] = Namespace("https://w3id.org/oc/ontology/")

    iri_entity: ClassVar[URIRef] = PROV.Entity
    iri_generated_at_time: ClassVar[URIRef] = PROV.generatedAtTime
    iri_invalidated_at_time: ClassVar[URIRef] = PROV.invalidatedAtTime
    iri_specialization_of: ClassVar[URIRef] = PROV.specializationOf
    iri_was_derived_from: ClassVar[URIRef] = PROV.wasDerivedFrom
    iri_had_primary_source: ClassVar[URIRef] = PROV.hadPrimarySource
    iri_was_attributed_to: ClassVar[URIRef] = PROV.wasAttributedTo
    iri_description: ClassVar[URIRef] = DCTERMS.description
    iri_has_update_query: ClassVar[URIRef] = OCO.hasUpdateQuery
```

Figure 14 ProvEntity class and provenance snapshots' properties according to the OpenCitations model.

- sparql. The Sparql class handles SPARQL queries. In particular, it searches on data or change-tracking metadata on the correct dataset in case information is stored on different sources. If there is more than one dataset, it queries each one, returning a single result. Finally, it allows querying both files and triplestores;
- support. It contains the empty_the_cache method, which allows freeing the cache and other private methods that are only useful for testing purposes.

Each of these modules works on the assumption that there are a dataset and some provenance. The files' location or the triplestore URL where that information resides is provided via a configuration file in JSON format, according to the pattern in figure Figure 15. In the most straightforward cases, everything is within the same source, whose position should be indicated both under the "dataset" and "provenance" headings. However, the library supports separate and multiple datasets and provenance sources, be they files or triplestores. In addition, it is possible to use mixed sources typologies for both the dataset and the provenance.

Furthermore, some optional values can be set to make executions faster and more efficient. As explained in chapter 5.3, to complete version structured queries including isolated triples, executing a textual search on deltas is necessary. Conveniently, Blazegraph allows full-text indexing and using predicates to do instant text searches, such as <http://www.bigdata.com/rdf/search#search>[6]. If

[6] For a complete guide on how to rebuild a testual index using Blazegraph, consult https://github.com/blazegraph/database/wiki/Rebuild_Text_Index_Procedure.

Blazegraph was used as a triplestore and a textual index was built, an affirmative boolean value must be set in the "blazegraph_full_text_search" field to take advantage of this feature.

It is worth noting that this, like all other entries in the configuration file, is explicit. The user should not remember the name of the setting; just set it. This choice was adopted because of the sixth heuristic by Jakob Nielsen, that is, to privilege recognition on recall (Nielsen 2005). Also, the second heuristic states that there must be a match between the system and the real world, then system-oriented terms should be avoided. Since Boolean logic may not be readily understood, the default value is "no", not "false". For the same reason, the library accepts a large number of values, converting them internally to True or False, namely: "true", "1", 1, "t", "y", "yes", "ok", "false", "0", 0, "n", "f", "no". Finally, the values are case insensitive to prevent possible errors, as the fifth heuristic explains.

To conclude the discussion on the configuration file's optional parameters, "cache_triplestore_url" allows specifying the URL of a triplestore to use as a cache. The benefits are at least three:

1. All past reconstructed graphs are saved on triplestore and never on RAM. Then, the impact of the process on the RAM is knocked down.
2. Time travel queries are executed on the cache triplestore and not on graphs saved in RAM. Therefore, they are faster.
3. If a query is launched a second time, the already recovered entities' history is not reconstructed but derived from the cache.

However, the cache also has two disadvantages. First, it takes up space. Secondly, the current implementation does not speed the relevant entities' discovery. The variables must be solved each time. If there are isolated triples, for example, all deltas must be queried every time.

```
{
        "dataset": {
                "triplestore_urls": [
                        "TRIPLESTORE_URL_1",
                        "TRIPLESTORE_URL_2",
                        "TRIPLESTORE_URL_N"
                ],
                "file_paths": ["PATH_1", "PATH_2", "PATH_N"]
        },
         "provenance": {
                "triplestore_urls": [
                        "TRIPLESTORE_URL_1",
                        "TRIPLESTORE_URL_2",
                        "TRIPLESTORE_URL_N"
                ],
                "file_paths": ["PATH_1", "PATH_2", "PATH_N"]
        },
        "blazegraph_full_text_search": "no",
        "cache_triplestore_url": "TRIPLESTORE_URL"
}
```

Figure 15 Configuration file's format.

Once the configuration parameters are set, it is essential to note that, among the mentioned modules, only agnostic_entity, agnostic_query and support are exposed to the user. On the contrary, prov_entity and sparql are exploited exclusively by the library itself. Therefore, the following paragraphs will focus on the first three to illustrate how to execute time agnostic queries, adopting the taxonomy by Fernández, Polleres, and Umbrich again (2015).

In order to materialize a version, an instance of the AgnosticEntity class must be created, passing an entity URI and the configuration file’s path as arguments. Finally, the get_state_at_time method ought to be run, providing a time of interest and, if provenance metadata is needed, True to the include_prov_metadata field (Figure 16).

```
agnostic_entity = AgnosticEntity(res=RES_URI, config_path=CONFIG_PATH)
agnostic_entity.get_state_at_time(time=(AFTER, BEFORE), include_prov_metadata=True)
```

Figure 16 Code to materialize an entity’s version.

The specified time is a tuple in the format (AFTER, BEFORE). If one of the two values is None, only the other is considered. The following examples show all possible combinations:

- ("2021-06-01", "2021-06-02T18:46"): it considers a time interval from 1 June 2021 to 2 June 2021 at 18:46.
- ("2021-06-01", None): it considers the snapshots after June 1, 2021.
- (None, "2021-06-01"): it considers the snapshots before June 1, 2021.
- ("2021-06-01", "2021-06-01"): it considers the snapshot of June 1, 2021.

Eventually, time can be specified using any format included in the ISO 8601 subset defined in the W3C note *Date and Time Formats* (Wolf and Wicksteed 1997).

The get_state_at_time output is always a tuple of three elements: the first is a dictionary that associates graphs and timestamps within the specified interval; the second contains the metadata of the snapshot that has been returned; the third is a dictionary including the other snapshots' provenance metadata if include_prov_metadata is True, None if False (Figure 17).

```
(
    {
        TIME_1: ENTITY_GRAPH_AT_TIME_1,
        TIME_2: ENTITY_GRAPH_AT_TIME_2
    },
    {
        SNAPSHOT_URI_AT_TIME_1: {
            'http://www.w3.org/ns/prov#generatedAtTime': TIME_1,
            'http://www.w3.org/ns/prov#wasAttributedTo': ATTRIBUTION,
            'http://www.w3.org/ns/prov#hadPrimarySource': PRIMARY_SOURCE
        },
        SNAPSHOT_URI_AT_TIME_2: {
            'http://www.w3.org/ns/prov#generatedAtTime': TIME_2,
            'http://www.w3.org/ns/prov#wasAttributedTo': ATTRIBUTION,
            'http://www.w3.org/ns/prov#hadPrimarySource': PRIMARY_SOURCE
        }
    },
    {
        OTHER_SNAPSHOT_URI_1: {
            'http://www.w3.org/ns/prov#generatedAtTime': GENERATION_TIME,
            'http://www.w3.org/ns/prov#wasAttributedTo': ATTRIBUTION,
            'http://www.w3.org/ns/prov#hadPrimarySource': PRIMARY_SOURCE
        },
        OTHER_SNAPSHOT_URI_2: {
            'http://www.w3.org/ns/prov#generatedAtTime': GENERATION_TIME,
            'http://www.w3.org/ns/prov#wasAttributedTo': ATTRIBUTION,
            'http://www.w3.org/ns/prov#hadPrimarySource': PRIMARY_SOURCE
        }
    }
)
```

Figure 17 Output of the get_state_at_time method.

On the other hand, if the whole history of a resource is required, the get_history method should be run (Figure 18). The class and the parameters are the same as get_state_at_time ones, but no interval is indicated because all times are needed. One might wonder why a new method was introduced instead of using the previous one by passing None as a period. The reason is that, as explained in 5.1, the two algorithms work differently for efficiency reasons. In addition, two functions indicating explicitly their purpose were preferred, rather than a single polyvalent one.

```
agnostic_entity = AgnosticEntity(res=RES_URI, config_path=CONFIG_PATH)
agnostic_entity.get_history(include_prov_metadata=True)
```

Figure 18 Code to materialize the whole history of an entity.

The output is different too and is always a two-element tuple. The first is a dictionary containing all the versions of a given resource. The second is a dictionary containing all the provenance metadata linked to that resource if include_prov_metadata is True, None if False. Figure 19 shows the output format.

```
(
  {
    RES_URI: {
      TIME_1: ENTITY_GRAPH_AT_TIME_1,
      TIME_2: ENTITY_GRAPH_AT_TIME_2
    }
  },
  {
    RES_URI: {
      SNAPSHOT_URI_AT_TIME_1: {
        'http://www.w3.org/ns/prov#generatedAtTime': GENERATION_TIME,
        'http://www.w3.org/ns/prov#wasAttributedTo': ATTRIBUTION,
        'http://www.w3.org/ns/prov#hadPrimarySource': PRIMARY_SOURCE
      },
      SNAPSHOT_URI_AT_TIME_2: {
        'http://www.w3.org/ns/prov#generatedAtTime': GENERATION_TIME,
        'http://www.w3.org/ns/prov#wasAttributedTo': ATTRIBUTION,
        'http://www.w3.org/ns/prov#hadPrimarySource': PRIMARY_SOURCE
      }
  }
)
```

Figure 19 Output of the get_history method.

Using a dictionary for the first output element may seem unnecessary since it consists of only one key. In reality, AgnosticEntity has an optional parameter, related_entities_history. If it is set to True, the get_history function returns the history of the entity indicated in the res field and all related ones. One resource is related to another when linked by an incoming connection rather than an outgoing one. In this case, the first element of the output tuple turns out to be a dictionary of as many keys as there are related entities plus the entity itself.

Proceeding, to perform a query on deltas, the DeltaQuery class must be instantiated, passing a SPARQL query string, a set of properties, and the configuration file’s path as arguments. The query string is helpful to identify the entities whose changes need to be investigated. It should be noted that the library only supports SELECT searches; therefore, CONSTRUCT, ASK or DESCRIBE searches are not allowed. At the same time, the predicates set narrows the field to those resources where the properties specified in the set have changed. If no property was indicated, any changes are considered. In addition, it is possible to indicate a time in the form of a tuple, with the same possibilities already described regarding version materialization. In that event, the query is executed on the specified range, otherwise on all dataset changes. Lastly, the run run_agnostic_query method should be run on the instantiated object, as shown in Figure 20.

```
agnostic_entity = DeltaQuery(
        query=QUERY_STRING,
        on_time=(AFTER, BEFORE),
        changed_properties=PROPERTIES_SET,
        config_path=CONFIG_PATH
)
agnostic_entity.run_agnostic_query()
```

Figure 20 Code to perform a single-delta structured query. Cross-delta structured queries only differ because the "on_time" field is equal to None.

The output is a dictionary that reports the modified entities when they changed and how they were modified, following the format in Figure 21. The modifications are reported as UPDATE SPARQL queries, in the same way as deltas are stored according to the OpenCitations Data Model.

```
{
  RES_URI_1: {
    TIMESTAMP_1: UPDATE_QUERY_1,
    TIMESTAMP_2: UPDATE_QUERY_2,
    TIMESTAMP_N: UPDATE_QUERY_N
  },
  RES_URI_2: {
    TIMESTAMP_1: UPDATE_QUERY_1,
    TIMESTAMP_2: UPDATE_QUERY_2,
    TIMESTAMP_N: UPDATE_QUERY_N
  },
  RES_URI_N: {
    TIMESTAMP_1: UPDATE_QUERY_1,
    TIMESTAMP_2: UPDATE_QUERY_2,
    TIMESTAMP_N: UPDATE_QUERY_N
  },
}
```

Figure 21 Output of a structured query on changes.

Finally, the VersionQuery class must be instantiated to make a single-version structured query, passing as an argument a SPARQL query string, a tuple representing the interval of interest, and the configuration file's path. Again, only SELECT searches are allowed. Ultimately, the run_agnostic_query method ought to be executed (Figure 22).

```
agnostic_query = VersionQuery(query=QUERY_STRING, on_time=(AFTER, BEFORE), config_path=CONFIG_PATH)
agnostic_query.run_agnostic_query()
```

Figure 22 Code to perform a single-version structured query.

The output is a dictionary where the keys are the snapshots relevant to that query within the input interval. The values correspond to sets of tuples containing the query results at the time specified by the key. The positional value of the elements in the tuples is equivalent to the variables indicated in the query (Figure 23).

```
{
   TIME: {
      (VALUE_1_OF_VARIABLE_1, VALUE_1_OF_VARIABLE_2, VALUE_1_OF_VARIABLE_N),
      (VALUE_2_OF_VARIABLE_1, VALUE_2_OF_VARIABLE_2, VALUE_2_OF_VARIABLE_N),
      (VALUE_N_OF_VARIABLE_1, VALUE_N_OF_VARIABLE_2, VALUE_N_OF_VARIABLE_N)
   }
}
```

Figure 23 Output of a single-version structured query.

On the other hand, if a cross-version structured query is needed, it is sufficient to specify no time. It is worth pointing out that the output of a cross-version structured query does not report all the dataset's snapshots but only those relevant to each of the resources involved in the query at each time. For example, suppose the user carries out the agnostic query in Figure 24. Reconstructing the history of <https://example/ra/1>, it turns out that it has two snapshots, one on May 7th, 2021, and the other on June 1st, 2021. Also, the resolution of the isolated triple on update queries shows that ?x corresponds to <https://example/ar/1> on 7th May 2021. However, it was deleted because of a merge with <https://example/ar/2> on 1st June 2021. Therefore, the times reported in output will be only 7th May 2021 and 1st June 2021.

```
query = """
            PREFIX pro: <http://purl.org/spar/pro/>
            SELECT DISTINCT ?x
            WHERE {
               ?x pro:isHeldBy <https://example/ra/1>.
            }
"""
agnostic_query = VersionQuery(query, config_path=CONFIG_PATH)
output = agnostic_query.run_agnostic_query()
# EXPECTED OUTPUT
# {
#     '2021-05-07T09:59:15': {
#         ('https://example/ar/1)
#     },
#     '2021-06-01T18:46:41': {
#         ('https://example/ar/2')
#     }
# }
```

Figure 24 Example of a cross-version structured query along with the corresponding output.

In the example of Figure 24, there is an isolated triple. In that event, as explained in 5.3, it is necessary to narrow the field by textual searches on deltas, which can be faster if Blazegraph was used as a triplestore, a textual index was reconstructed, and a positive boolean value was passed in the "blazegraph_full_text_search" field. To concretely exploit that index, it is also necessary to adopt the BlazegraphQuery class instead of VersionQuery, both for single-version and for cross-version structured queries. Apart from this difference, their usage is identical.

7 LIBRARY IMPLEMENTATION

Only nerds are allowed.

8 DISCUSSION

Benchmark e confronto con soluzioni esistenti.

9 CONCLUSION

Ricapitolo tutto.

10 REFERENCES

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