Piecing the puzzle
Self-publishing queryable research data on the Web

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The original article is available at https://ruben.verborgh.org/articles/queryable-research-data/.

ABSTRACT

Publishing research on the Web accompanied by machine-readable data is one of the aims of Linked Research. Merely embedding metadata as RDFa in HTML research articles, however, does not solve the problems of accessing and querying that data. Hence, I created a simple ETL pipeline to extract and enrich Linked Data from my personal website, publishing the result in a queryable way through Triple Pattern Fragments. The pipeline is open source, uses existing ontologies, and can be adapted to other websites. In this article, I discuss this pipeline, the resulting data, and its possibilities for query evaluation on the Web. More than 35,000 RDF triples of my data are queryable, even with federated SPARQL queries because of links to external datasets. This proves that researchers do not need to depend on centralized repositories for readily accessible (meta-)data, but instead can—and should—take matters into their own hands.

INTRODUCTION

The World Wide Web continues to shape many domains, and not in the least research. On the one hand, the Web beautifully fulfills its role as a *distribution channel* of scientific knowledge, for which it was originally invented. This spurs interesting dialogues concerning Open Access [1] and even piracy [2] of research articles. On the other hand, the advent of *social networking* creates new interaction opportunities for researchers, but also forces us to consider our online presence [3]. Various social networks dedicated to research have emerged: Mendeley, ResearchGate, Academia, … They attract millions of researchers, and employ various tactics to keep us there.

A major issue of these social research networks is their *lack of mutual complementarity*. None of them has become a clear winner in terms of adaption. At first sight, the resulting plurality seems a blessing for diversity, compared to the monoculture of Facebook for social networking in general. Yet whereas other generic social networks such as Twitter and LinkedIn serve complementary professional purposes compared to Facebook, social *research* networks share nearly identical goals. As an example, a researcher could announce a newly accepted paper on Twitter, discuss its review process on Facebook, and share a photograph of an award on LinkedIn. In contrast, one would typically not exclusively list a specific publication on Mendeley and another on Academia, as neither publication list would be complete.

In practice, this results in constant bookkeeping for researchers who want each of their profiles to correctly represent them—a necessity if such profiles are implicitly or explicitly treated as performance indicators [4]. Deliberate absence on any of these networks is not a viable option, as parts of one's publication metadata might be automatically harvested or entered by co-authors, leaving an automatically generated but incomplete profile. Furthermore, the quality of such non-curated metadata records can be questionable. As a result, researchers who do not actively maintain their online research profiles risk ending up with *incomplete* and *inaccurate* publication lists on those networks. Such misrepresentation can be significantly worse than not being present at all—but given the public nature of publication metadata, complete absence is not an enforceable choice.

Online representation is not limited to social networks: scientific publishers also make metadata available about their journals and books. For instance, Springer Nature recently released SciGraph, a Linked Open Data platform that includes scholarly metadata. *Accuracy* is less of an issue in such cases, as data comes directly from the source. However, *quality* and *usability* are still influenced by the way data is modeled and whether or how identifiers are disambiguated. *Completeness* is not guaranteed, given that authors typically target multiple publishers. Therefore, even such authoritative sources do not provide individual researchers with a correct profile.

In the spirit of decentralized social networking [5] and Linked Data [6], several researchers instead started publishing their own data and metadata. I am one of them, since I believe in practicing what we preach [7] as Linked Data advocates, and because I want my own website to act as the main authority for my data. After all, I can spend more effort on the completeness and accuracy of my publication metadata than most other platforms could reasonably do for me. In general, self-published data typically resides in separate RDF documents [8] (for which the FOAF vocabulary [9] is particularly popular [10]), or inside of HTML documents (using RDFa Lite [11] or similar formats).

Despite the controllable quality of personally maintained research data and metadata in individual documents on the Web, they are not as *visible*, *findable*, and *queryable* as those of social research networks. I call a dataset interface "queryable" with respect to a given query when a consumer does not need to download the entire dataset in order to evaluate that query over it with full completeness. Unfortunately, hosting advanced search interfaces on a personal website quickly becomes complex and expensive. To mitigate this, I have implemented a simple *Extract/Transform/Load (ETL) pipeline* on top of my personal website, which extracts, enriches, and publishes my Linked Data in a queryable way through a Triple Pattern Fragments [12] interface. The resulting data can be browsed and queried live on the Web, with higher quality and flexibility than on my other online profiles, and at only a limited cost for me as data publisher.

This article describes my use case, which resembles that of many other researchers. I detail the design and implementation of the ETL pipeline, and report on its results. At the end, I list open questions regarding self-publication, before concluding with a reflection on the opportunities for the broader research community.

USE CASE

Available Data

Like the websites of many researchers, my personal website contains data about the following types of resources:

- people such as colleagues, collaborators, and fellow researchers
- research articles I have co-authored
- blog posts I have written
- courses I teach

This data is spread across different HTTP resources:

- a single RDF document (FOAF profile) containing:
  - manually entered data *(personal data, affiliations, projects)*
  - automatically generated metadata *(publications, blog posts)*
- an HTML page with RDFa per:
  - publication *(publication and author metadata)*
  - blog post *(post metadata)*
  - HTML article *(metadata and citations)*
  - …

Depending on the context, I encode the information with different vocabularies:

- Friend of a Friend (FOAF) *(people, documents)*
- Schema.org *(blog posts, articles, courses)*
- Bibliographic Ontology (BIBO) *(publications)*
- Citation Typing Ontology (CiTO) *(citations)*
- …

There is a considerable amount of *overlap* since much data is available in more than one place, sometimes in different vocabularies. For example, webpages about my publications contain Schema.org markup (to facilitate indexing by search engines), whereas my profile describes the same publications more rigorously using BIBO and FOAF (for more advanced RDF clients). I deliberately reuse the same identifiers for the same resources everywhere, so identification is not an issue.

Data Publication Requirements

While the publication of structured data as RDF and RDFa is conveniently integrated in the webpage creation process, *querying information over the entire website* is difficult. For instance, starting from the homepage, obtaining a list of all mentioned people on the website would be non-trivial. In general, SPARQL query execution over Linked Data takes a considerable amount of time, and completeness cannot be guaranteed [13]. So while Linked Data documents are excellent for automated exploration of individual resources, and for aggregators such as search engines that can harvest the entire website, the possibilities of individual automated clients remain limited.

Another problem is the *heterogeneity of vocabularies*: clients without reasoning capabilities would only find subsets of the information, depending on which vocabulary is present in a given representation. Especially in RDFa, it would be cumbersome to combine every single occurrence of `schema:name` with the semantically equivalent `dc:title`, `rdfs:label`, and `foaf:name`. As such, people might have a `foaf:name` (because FOAF is common for people), publications a `schema:name` (because of `schema:ScholarlyArticle`), and neither an `rdfs:label`. Depending on the kind of information, queries would thus need different predi-

cates for the concept "label". Similarly, queries for `schema:Article` or `schema:CreativeWork` would not return results because they are not explicitly mentioned, even though their subclasses `schema:BlogPosting` and `schema:ScholarlyArticle` appear frequently.

Given the above considerations, the constraints of individual researchers, and the possibilities of social research networks, we formulate the following requirements:

- Automated clients should be able to evaluate **queries with full completeness** with respect to the data on the website.
- **Semantically equivalent expressions** should yield the same query results, **regardless of vocabulary** with respect to all vocabularies used on the website.
- Queryable data can only involve a **limited cost and effort** for publishers as well as consumers.

ETL PIPELINE

To automate this process, I have developed a simple ETL pipeline. With the exception of a couple of finer points, the pipeline itself is fairly straightforward. What is surprising, however, is the impact such a simple pipeline can have, as discussed hereafter in the Results section. The pipeline consists of the following phases, which will be discussed in the following subsections.

- **Extract** all triples from the website's RDF and HTML+RDFa documents.
- **Reason** over this data and its ontologies to complete gaps.
- **Publish** the resulting data in a queryable interface.

The source code for the pipeline is available on GitHub. The pipeline can be run periodically, or triggered on website updates as part of a continuous integration process. In order to adapt this to different websites, the default ontology files can be replaced by others that are relevant for a given website.

Extract

The pipeline loops through all of the website's files (either through the local filesystem or through Web crawling) and makes lists of RDF documents and HTML+RDFa documents. The RDF documents are fed through the Serd parser to verify validity and for conversion into N-Triples [14], so the rest of the pipeline can assume one triple per line. The RDFa is parsed into N-Triples by the RDFLib library for Python. Surprisingly, this library was the only one I found that correctly parsed RDFa Lite in (valid) HTML5; both Raptor and Apache Any23 seemed to expect a stricter document layout.

Reason

In order to fix gaps caused by implicit properties and classes, the pipeline performs reasoning over the extracted data and its ontologies to compute the deductive closure. The choice of ontologies is based on the data, and currently includes FOAF, DBpedia, CiTO, Schema.org, and the Organizations ontology. Additionally, I specified a limited number of custom OWL triples to indicate equivalences that hold on my website, but not necessarily in other contexts.

The pipeline delegates reasoning to the highly performant EYE reasoner [15], which does not have any RDFS or OWL knowledge built-in. Consequently, relevant RDFS and OWL theories can be selected manually, such that only a practical subset of the entire deductive closure is computed. For instance, my FOAF profile asserts that all resources on my site are different using

`owl:AllDifferent`; a full deductive closure would result in an undesired combinatorial explosion of `owl:differentFrom` statements.

The website's dataset is enriched through the following steps:

1. The ontologies are **skolemized [8]** and concatenated into a single ontology file.

2. The **deductive closure of the joined ontology** is computed by passing it to the EYE reasoner with the RDFS and OWL theories.

3. The **deductive closure of the website's data** is computed by passing it to the EYE reasoner with the RDFS and OWL theories and the deductive closure of the ontology.

4. **Ontological triples are removed from the data** by subtracting triples that also occur in the deductive closure of the ontology.

5. **Other unnecessary triples are removed**, in particular triples with skolemized ontology IRIs, which are meaningless without the ontology.

These steps ensure that only triples directly related to the data are published without any direct or derived triples from its ontologies, which form different datasets. By separating them, ontologies remain published as independent datasets, and users executing queries can explicitly choose which ontologies or datasets to include.

For example, when the original data contains
`art:publication schema:author rv:me.`
and given that DBpedia and Schema.org ontologies (before skolemization) contain
```
dbo:author owl:equivalentProperty schema:author.
schema:author rdfs:range [
  owl:unionOf (schema:Organization schema:Person
].
```
then the raw reasoner output of step 3 (after skolemization) would be
```
art:publication dbo:author rv:me.
art:publication schema:author rv:me.
rv:me rdf:type skolem:b0.
dbo:author owl:equivalentProperty schema:author.
schema:author rdfs:range skolem:b0.
skolem:b0 owl:unionOf skolem:l1.
skolem:l1 a rdf:List.
skolem:l1 rdf:first schema:Organization.
skolem:l1 rdf:rest  skolem:l2.
skolem:l2 a rdf:List.
skolem:l2 rdf:first schema:Person.
skolem:l2 rdf:rest  rdf:nil.
```
The skolemization in step 1 ensures that blank nodes from ontologies have the same identifier before and after the reasoning runs in steps 2 and 3. Step 2 results in triples 9–17 (note the inferred triples 12 and 15), which are also present in the output of step 3, together with the added triples 6–8 derived from data triple 1. Because of the previous skolemization, triples 9–16 can be removed through a simple line-by-line difference, as they have identical N-Triples representations in the outputs of steps 2 and 3. Finally, step 5 removes triple 8, which is not meaningful as it points to an unreferenceable blank node in the Schema.org ontology. The resulting enriched data is:
```
art:publication dbo:author rv:me.
art:publication schema:author rv:me.
```
Thereby, data that was previously only described with Schema.org in RDFa becomes also available with DBpedia. Note that the example triple yields several more triples in the actual pipeline, which uses the full FOAF, Schema.org, and DBpedia ontologies.

Passing the deductive closure of the joined ontology from step 2 to step 3 improves performance, as the derived ontology triples are already materialized. Given that ontologies change slowly, the output of steps 1 and 2 could be cached.

Publish

The resulting triples are then published through a Triple Pattern Fragments (TPF) [12] interface, which allows clients to access a dataset by triple pattern. In essence, the lightweight TPF interface extends Linked Data's subject-based dereferencing by also providing predicate- and object-based lookup. Through this interface, clients can execute SPARQL queries with full completeness at limited server cost. Because of the simplicity of the interface, various back-ends are possible. For instance, the data from the pipeline can be served from memory by loading the generated N-Triples file, or the pipeline can compress it into a Header Dictionary Triples (HDT) [16] file.

Special care is taken to make IRIs dereferenceable [6] during the publication process. While I emphasize IRI reuse, some of my co-authors do not have their own profile, so I had to mint IRIs for them. Resolving such IRIs results in an HTTP `303` redirect to the TPF with data about the concept. For instance, the IRI `https://data.verborgh.org/people/sam_coppens` redirects to the TPF of triples with this IRI as subject.

RESULTS

I applied the ETL pipeline to my personal website https://ruben.verborgh.org/ to verify its effectiveness. The data is published at https://data.verborgh.org/ruben and can be queried with a TPF client such as http://query.verborgh.org/. The results reflect the status of January 2017, and measurements were executed on a MacBook Pro with a 2.66GHz Intel Core i7 processor and 8GB of RAM.

Generated Triples

In total, 35,916 triples were generated in under 5 minutes from 6,307 profile triples and 12,564 unique triples from webpages. The table below shows the number of unique triples at each step and the time it took to obtain them. The main bottleneck is *not* reasoning (≈3,000 triples per second), but rather RDFa extraction (≈100 triples per second), which can fortunately be parallelized more easily.

step	time (s)	# triples
RDF(a) extraction	170.0	17,050
ontology skolemization	0.6	44,179
deductive closure ontologies	38.8	144,549
deductive closure data and ontologies	61.8	183,282
subtract ontological triples	0.9	38,745
subtract other triples	1.0	35,916
total	273.0	35,916

Table 1: The number of unique triples per phase, and the time it took to extract them.

While dataset size is not an indicator for quality [17], the accessibility of the data improves through the completion of inverse predicates and equivalent or subordinate predicates and classes between ontologies. The table below lists the frequency of triples with specific predicates and classes before and after executing the pipeline.

predicate or class	# pre	# post
`dc:title`	657	714
`rdfs:label`	473	714
`foaf:name`	394	714
`schema:name`	439	714
`schema:isPartOf`	263	263
`schema:hasPart`	0	263
`cito:citesAsAuthority`	14	14
`cito:cites`	0	33
`schema:citation`	0	33
`foaf:Person`	196	196
`dbo:Person`	0	196
`schema:ScholarlyArticle`	203	203
`schema:Article`	0	243
`schema:CreativeWork`	0	478

Table 2: The number of triples with the given predicate or class before and after the execution of the pipeline, grouped by semantic relatedness.

It is important to note that most improvements are solely the result of reasoning on existing ontologies; only 8 custom OWL triples were added (7 for equivalent properties, 1 for a symmetric property).

Quality

While computing the deductive closure should not introduce any inconsistencies, the quality of the ontologies directly impacts the result. While inspecting the initial output, I found the following conflicting triples, typing me as a person *and* a company:

```
rv:me rdf:type dbo:Person.
rv:me rdf:type dbo:Company.
```

To find the cause of this inconsistency, I ran the reasoner on the website data and ontologies, but instead of asking for the deductive closure, I asked to prove the second triple. The resulting proof traced the result back to the DBpedia ontology erroneously stating the equivalence of the `schema:publisher` and `dbo:first-Publisher` properties. While the former has both people and organisations in its range, the latter is specific to companies—hence the conflicting triple in the output. I reported this issue and manually corrected it in the ontology. Similarly, `dbo:Website` was deemed equivalent to `schema:WebPage`, whereas the latter should be `schema:WebSite`. Disjointness constraints in the ontologies would help catch these mistakes. Further validation with RDFUnit [18] brought up a list of errors, but all of them turned out to be false positives.

Queries

Finally, I report on the execution time and number of results for a couple of example SPARQL queries. These were evaluated against the live TPF interface by a TPF client, and against the actual webpages and profile by a Linked Data-traversal-based client (SQUIN [19]). The intention is *not* to compare these query engines, as they use different paradigms and query semantics: TPF guarantees 100% completeness with respect to given datasets, whereas SQUIN considers reachable subwebs. The goal is rather to highlight the limits of querying over RDFa pages as practiced today, and to contrast this with the improved dataset resulting from the ETL pipe-

line.

To this end, I tested three scenarios on the public Web:

1. a Triple Pattern Fragments client (ldf-client 2.0.4) with the pipeline's TPF interface
2. a Linked Data client (SQUIN 20141016) with my homepage as seed
3. a Linked Data client (SQUIN 20141016) with my FOAF profile as seed

All clients started with an empty cache for every query, and the query timeout was set to 60 seconds. The waiting period between requests for SQUIN was disabled. For the federated query, the TPF client also accessed DBpedia, which the Linked Data client can find through link traversal. To highlight the impact of the seeds, queries avoid IRIs from my domain by using literals for concepts instead.

query	TPF *(pipe-line)*		LD *(home)*		LD *(pro-file)*	
	#	t (s)	#	t (s)	#	t (s)
people I know (`foaf:name`)	196	2.1	0	5.6	14	60.0
people I know (`rdfs:label`)	196	2.1	0	3.2	200	60.0
publications I wrote	205	4.0	0	10.8	0	10.5
my publications	205	4.1	134	12.6	134	14.4
my blog posts	43	1.1	40	6.5	40	6.4
my articles	248	4.9	0	6.3	0	3.3
a colleague's publications	32	1.1	20	13.9	20	16.3
my first-author publications	46	2.7	0	3.8	6	36.2
works I cite	46	0.5	0	4.0	0	60.0
my interests *(federated)*	4	0.4	0	4.0	4	1.8

Table 3: Number of results and execution time per query, comparing the TPF client on the enhanced data with Linked Data traversal on my website (starting from my home page or my FOAF profile).

The first two queries show the influence of *ontological equivalences*. At the time of writing, my website related me to 196 `foaf:Person`s through the `foaf:knows` predicate. If the query uses only the FOAF vocabulary, with `foaf:name` to obtain people's names, Linked Data traversal finds 14 results. If we use `rdfs:label` instead, it even finds additional results on external websites (because of link-traversal query semantics).

A second group of queries reveals the impact of *link unidirectionality* and inference of *subclasses and subproperties* in queries for scholarly publications and blog posts. Through traversal, *"publications I wrote"* (with `foaf:made`) does not yield any results, whereas *"my publications"* (with `schema:author`) yields 134, even though both queries are semantically equivalent. Given that my profile actually contained 205 publications, the 71 missing publications are caused by SQUIN's implementation rather than being an inherent Linked Data limitation. Blog posts are found in all scenarios, even though the traversal client finds 3 fewer posts. Only the TPF client is able to find all articles, because the pipeline generated the inferred type `schema:Article` for publications and blog

posts. Other more constrained queries for publications yield fewer results through traversal as well. Citations (`cito:cites`) are only identified by the TPF client, as articles solely mention its subproperties.

The final test examines a *federated query:* when starting from the profile, the Linked Data client also finds all results.

Regarding execution times, the measurements provide positive signals for low-cost infrastructures on the public Web. Note that both clients return results *iteratively*. With an average arrival rate of 53 results per second for the above queries, the TPF client's pace exceeds the processing capabilities of people, enabling usage in live applications. Even faster performance could be reached with, for instance, a data dump or a SPARQL endpoint; however, these would involve an added cost for either the data publisher or consumer, and might have difficulties in federated contexts.

OPEN QUESTIONS

Publishing RDFa data on my website over the past years—and subsequently creating the above pipeline—has left me with a couple of questions, some of which I discuss below.

A first question is *what* data should be encoded as Linked Data, and how it should be *distributed* across resources. In the past, I always had to decide whether to write data directly on the page as HTML+RDFa, whether to place it in my FOAF profile as RDF, whether to do both, or neither. The pipeline partially solves the *where* problem by gathering all data in a single interface. Even though each page explicitly links to the Linked Data-compatible TPF interface using `void:inDataset`—so traversal-based clients can also consume it—other clients might only extract the triples from an individual page. Furthermore, apart from the notable exception of search engine crawlers, it is hard to predict what data automated clients are looking for.

A closely related question is *what ontologies* should be used on which places. Given that authors have limited time and in order to not make HTML pages too heavy, we should probably limit ourselves to a handful of vocabularies. When inter-vocabulary links are present, the pipeline can then materialize equivalent triples automatically. I have chosen Schema.org for most HTML pages, as this is consumed by several search engines. However, this vocabulary is rather loose and might not fit other clients. Perhaps the FOAF profile is the right place to elaborate, as this is a dedicated RDF document that attracts more specific-purpose clients compared to regular HTML pages.

Even after the above choices have been made, the *flexibility* of some vocabularies leads to additional decisions. For example, in HTML articles I mark up citations with the CiTO ontology. The domain and range of predicates such as `cito:cites` is open to documents, sections, paragraphs, and other units of information. However, choosing to cite an article from a paragraph influences how queries such as "citations in my articles" need to be written. Fortunately, the pipeline can infer the other triples, such that the section and document containing the paragraph also cite the article.

When marking up data, I noticed that I sometimes attach *stronger meaning* to concepts than strictly prescribed by their ontologies. Some of these semantics are encoded in my custom OWL triples, whose contents contribute to the reasoning process (but do not appear directly in the output, as this would leak my semantics globally). For instance, I assume equivalence of `rdfs:label` and `foaf:name` for my purposes, and treat the `foaf:knows` relation as symmetrical (as in its textual—but not formal—definition). Us-

ing my own subproperties in these cases would encode more specific semantics, while the other properties could be derived from the pipeline. However, this would require maintaining a custom ontology, to which few queries would refer.

The *reuse of identifiers* is another source of debate. I opted as much as possible to reuse URLs for people and publications. The advantage is that this enables Linked Data traversal, so additional RDF triples can be picked up from FOAF profiles and other sources. The main drawback, however, is that the URLs do not dereference to my own datasource, which *also* contains data about their concepts. As a result, my RDF data contains a mix of URLs that dereference externally (such as http://csarven.ca/#i), URLs that dereference to my website (such as https://ruben.verborgh.org/articles/queryable-research-data/) and URLs that dereference to my TPF interface (such as https://data.verborgh.org/people/anastasia_dimou) Fortunately, the TPF interface can be considered an extension of the Linked Data principles [20], such that URLs can be "dereferenced" (or queried) on different domains as well, yet this not help regular Linked Data crawlers. An alternative is using my own URLs everywhere and connecting them with external URLs through `owl:sameAs`, but then certain results would only be revealed to more complex SPARQL queries that explicitly consider multiple identifiers.

With regard to publishing, I wondered to what extent we should place RDF triples in the *default graph* on the Web at large. As noted above, inconsistencies can creep in the data; also, some of the things I state might reflect my beliefs rather than general truths. While RDFa does not have a standardized option to place data in named graphs, other types of RDF documents do. By moving my data to a dedicated graph, as is practiced by several datasets, I could create a separate context for these triples. This would also facilitate provenance and other applications, and it would then be up to the data consumer to decide how to treat data graph.

The above questions highlight the need for *guidance* and *examples* in addition to specifications and standards. *Usage statistics* could act as an additional information source. While HTTP logs from the TPF interface do not contain full SPARQL queries, they show the IRIs and triple patterns clients look for. Such behavioral information would not be available from clients or crawlers visiting HTML+RDFa pages.

Finally, when researchers start self-publishing their data in a queryable way at a large scale, we will need a *connecting layer* to approach the decentralized ecosystem efficiently through a single user interface. While federated query execution over multiple TPF interfaces on the public Web is feasible, as demonstrated above, this mechanism is impractical to query hundreds or thousands of such interfaces. On the one hand, this indicates their will still be room for centralized indexes or aggregators, but their added value then shifts from data to services. On the other hand, research into decentralized technologies might make even such indexes obsolete.

CONCLUSION

RDFa makes semantic data *publication* easy for researchers who want to be in control of their online data and metadata. For those who prefer not to work directly on RDFa, or lack the knowledge to do so, annotation tools and editors can help with its *production*. In this article, I examined the question of how we subsequently can optimize the *queryability* of researchers' data on the Web, in order to facilitate their *consumption* by different kinds of clients.

Simple clients do not possess the capabilities of large-scale aggregators to obtain all Linked Data on a website. They encounter

mostly individual HTML+RDFa webpages, which are always incomplete with respect to both the whole of knowledge on a website as well as the ontological constructs to express it. Furthermore, variations in reasoning capabilities make bridging between different ontologies difficult. The proposed ETL pipeline addresses these challenges by publishing a website's explicit and inferred triples in a queryable interface. The pipeline itself is simple and can be ported to different scenarios. If cost is an issue, the extraction and reasoning steps can run on public infrastructures such as Travis CI, as all involved software is open source. Queryable data need not be expensive either, as proven by free TPF interfaces on GitHub [21] and by the LOD Laundromat [22], which provides more than 600,000 TPF interfaces on a single server.

By publishing queryable research data, we contribute to the Linked Research vision: the proposed pipeline increases reusability and improves linking by completing semantic data through reasoning. The possibility to execute live queries—and in particular federated queries—enables new use cases, offering researchers additional incentives to self-publish their data. Even though I have focused on research data, the principles generalize to other domains. In particular, the Solid project for decentralized social applications could benefit from a similar pipeline to facilitate data querying and exchange across different parties in a scalable way.

Even as a researcher who has been publishing RDFa for years, I have often wondered about the significance of adding markup to individual pages. I doubted to what extent the individual pieces of data I created contributed to the larger puzzle of Linked Data on my site and other websites like it, given that they only existed within the confines of a single page. Building the pipeline enabled the execution of complex queries across pages, without significantly changing the maintenance cost of my website. From now on, every piece of data I mark up directly leads to one or more queryable triples, which provides me with a stronger motivation. If others follow the same path, we no longer need centralized data stores. We could execute federated across researchers' websites, using combinations of Linked Data traversal and more complex query interfaces that can guarantee completeness. Centralized systems can play a crucial role by providing indexing and additional services, yet they should act at most as secondary storage.

Unfortunately, exposing my own data in a queryable way does not relieve me yet of my frustration of synchronizing that data on current social research networks. It does make my data more searchable and useful though, and I deeply hope that one day, these networks will synchronize with my interface instead of the other way round. Most of all, I hope that others will mark up their webpages and make them queryable as well, so we can query research data on the *Web* instead of in silos. To realize this, we should each contribute our own pieces of data in a way that makes them fit together easily, instead of watching third parties mash our data into an entirely different puzzle altogether.

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