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LSQ 2.0: A linked dataset of SPARQL query logs

Claus Stadler [a,*], Muhammad Saleem [a], Qaiser Mehmood [b], Carlos Buil-Aranda [c], Michel Dumontier [d], Aidan Hogan [e] and Axel-Cyrille Ngonga Ngomo [a]

[a] *Universität Leipzig, IFI/AKSW, PO 100920, D-04009, Leipzig*
[b] *Insight Center for Data Analytics, National University of Ireland, Galway*
[c] *IMFD; Informatics Department, Universidad Técnica Federico Santa María, Chile*
[d] *Institute of Data Science, Maastricht University, Maastricht, The Netherlands*
[e] *IMFD; Department of Computer Science, University of Chile, Santiago, Chile*

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Abstract. We present the Linked SPARQL Queries (LSQ) dataset, which currently describes 43.95 million executions of 11.56 million unique SPARQL queries extracted from the logs of 27 different endpoints. The LSQ dataset provides RDF descriptions of each such query, which are indexed in a public LSQ endpoint, allowing interested parties to find queries with the characteristics they require. We begin by describing the use cases envisaged for the LSQ dataset, which include applications for research on common features of queries, for building custom benchmarks, and for designing user interfaces. We then discuss how LSQ has been used in practice since the release of four initial SPARQL logs in 2015. We discuss the model and vocabulary that we use to represent these queries in RDF. We then provide a brief overview of the 27 endpoints from which we extracted queries in terms of the domain to which they pertain and the data they contain. We provide statistics on the queries included from each log, including the number of query executions, unique queries, as well as distributions of queries for a variety of selected characteristics. We finally discuss how the LSQ dataset is hosted and how it can be accessed and leveraged by interested parties for their use cases.

Keywords: SPARQL, Query Log Analysis, Web of Data, RDF

1. Introduction

Since its initial recommendation in 2008 [70], the SPARQL query language for RDF has received considerable adoption, where it is used on hundreds of public query endpoints accessible over the Web [93]. The most prominent of these endpoints receive millions of queries per month [12], or even per day [57]. There is much to be learnt from queries received by such endpoints, where research on SPARQL would benefit – and has already benefited – from access to real-world queries to help focus both applied and theoretical research on commonly seen forms of queries [59].

To exemplify how access to real-world queries can directly benefit research on SPARQL, first consider the complexity results of SPARQL [67], which show that evaluation of SPARQL queries is intractable (PSPACE-hard). But do the worst cases predicted in theory actually occur in practice? Is it possible to define *fragments* of the language

*Corresponding author. E-mail: cstadler@informatik.uni-leipzig.de.

that avoid computationally difficult cases and lead the way to efficient algorithms dedicated to these common cases? The answer is yes, where a number of restricted fragments of SPARQL queries have been identified that are less computationally costly for important tasks. These fragments include *well-designed queries* that use the `OPTIONAL` clause in restricted ways [21,67], queries with *low treewidth* [21] whose structure is close to that of a tree, queries such as *simple transitive expressions* [58] or (certain fragments of) *simple conjunctive regular path queries* [36] where only restricted use of Kleene star ($\star$) is allowed in path expressions, certain types of *simple conjunctive regular path queries* where disjunction ($|$) is not allowed inside Kleene star, and *threshold queries* that limit the number of results returned [20]. Studies of SPARQL query logs have shown that these fragments cover many of the queries seen in practice [24,58], where query logs help to bridge the theory and practice of SPARQL [59].

Another use case for a large collection of real-world queries pertains to benchmarking. For over a decade, the SPARQL community has relied on synthetic datasets and queries (e.g., LUBM [40], Berlin [19]), or real-world datasets and hand-crafted queries (e.g., BTC [63], FedBench [84]) to perform benchmarking. However, Aluç et al. [7] and Saleem et al. [83] find the queries of these benchmarks to often be too narrow and simplistic. Building *benchmarks* from real-world queries can help tune implementations and guide research towards better support for the types of queries most commonly encountered in practical settings [13,16,62,65,79,101]. Yet another use case is *caching* [50,54,100]. Here, real-world queries can be used to simulate practical workloads experienced by endpoints. The *usability* of SPARQL interfaces [24,25,52,73] can also benefit from query logs, as these logs can reveal patterns in how users incrementally build their queries, as has recently been studied by Bonifati et al. [24] in DBpedia logs. These use cases and others will be discussed in more detail in Section 2.

Recognising the value of query logs, a number of such collections have been published previously, including contributions from USEWOD [55],[1] as well as Wikidata [57]. These logs have been widely used and analysed by a variety of authors (e.g., [12,21,23,57,68,72]). However, (i) these logs are provided in ad-hoc formats, varying in terms of syntax and information provided depending on the particular SPARQL implementation used to host the endpoint. (ii) Typically, queries are published as strings, meaning (for example) that a client would need to use a SPARQL query parser and some procedural code to find queries matching particular structures or characteristics. (iii) Moreover, runtime statistics in terms of–for example–the selectivity of individual query patterns with respect to the base dataset of the endpoint are not provided. (iv) Furthermore, these datasets have generally been limited to publishing logs from a small number (1–4) of endpoints.

In this dataset description paper, we extend upon our previous work [77], which reported on the initial release of the Linked SPARQL Query Dataset (LSQ). The goal of LSQ is to publish queries from a variety of SPARQL logs in a consistent format and associate these queries with rich metadata, including both static metadata (i.e., considering only the query) and runtime metadata (i.e., considering the query and the dataset). In particular, we propose an RDF representation of queries that captures their source, structure, static metadata and runtime metadata. These RDF descriptions of queries are indexed in a SPARQL endpoint. Thus, they allow clients to retrieve the queries of interest to their use case declaratively, potentially sourced from several endpoints at once. In comparison to our previous work [77], which described the initial release of the dataset in 2015:

– The LSQ dataset has grown considerably: LSQ 2.0 now features logs from 27 endpoints (22 of which are from Bio2RDF) compared with 4 initial endpoints. As a result, the number of query executions described by the LSQ 2.0 dataset has grown from 5.68 million to 43.95 million.
– Based on the experiences gained from the first version of LSQ, we have improved the RDF model to provide better modularisation and more detailed metadata, facilitating new ways in which clients can select the queries of interest to them; we have likewise updated the LSQ vocabulary accordingly.
– We have re-engineered the extraction framework, which takes as input raw logs produced by a variety of popular SPARQL engines and Web servers, producing an output RDF graph in the LSQ 2.0 data model describing the queries. The RDFization process can now be scaled as it leverages Apache Spark.[2] The LSQ software framework has been released as open source.

[1] http://usewod.org/; retr. 2015/04/14.
[2] https://spark.apache.org/

- We have evaluated the new queries locally in a Virtuoso instance in order to gain runtime statistics (including estimates of the number of results, the selectivity of patterns, overall runtimes, etc.), and have updated the statistical analysis of the queries featured by LSQ to include the additional data provided by the new endpoints.
- Since the initial release, LSQ has been used by a variety of diverse research works on SPARQL [2,3,11,14,15,17,18,21,22,26,30–32,34,35,37,39,41,42,49,58,69,71,74–76,78–80,83,85–87,89–91,94,97–99,102]. To exemplify the value of LSQ, we discuss the various ways in which the dataset has been used in these past years.

LSQ 2.0 is available at http://aksw.github.io/LSQ/.

The rest of the paper is structured as follows:

- Section 2 describes use cases envisaged for LSQ.
- Section 3 details the model and vocabulary used by LSQ to represent and describe SPARQL queries.
- Section 4 describes how LSQ is published following Linked Data principles and best practices.
- Section 5 first describes the datasets for which LSQ indexes queries, and then provides details on the raw logs from which queries are extracted.
- Section 6 provides an analysis of the LSQ dataset itself, as well as the queries it contains.
- Section 7 describes how LSQ has been adopted for the past six years since its initial release.
- Section 8 concludes and discusses future directions for the LSQ dataset.

2. Use cases

To help motivate the Linked SPARQL Queries dataset, we first discuss some potential use cases that we envisage. We then list some general requirements for LSQ that arise from these use cases.

UC1 Custom Benchmarks A number of benchmarks have been proposed recently based on real-world queries observed in logs [16,62,79,101]. The LSQ dataset can support the creation of such benchmarks, allowing users to select queries from a diverse selection of logs based on custom criteria matching the metadata provided by LSQ. Queries may be selected so as to provide a general benchmark that is representative of real-world workloads, or a specialised benchmark focused on particular query characteristics, such as path expressions, multi-way joins, and aggregation queries.

UC2 SPARQL Adoption Various works have analysed SPARQL query logs in order to understand how features of the SPARQL standard are used "in the wild" as well as to extract structural properties of real-world queries [12,21,23,24,57,68,72]. In turn, this family of works has led to the definition of tractable fragments of queries that are common in practice [20,58]. LSQ can facilitate further research on the use of SPARQL in the wild as it compiles logs from different domains.

UC3 Caching Techniques for SPARQL caching [50,60,66,100] aim to re-use solutions across multiple queries. Caching allows for reducing the computational requirements needed to evaluate a workload, particularly in cases where queries are often repeated and the underlying data do not change too frequently. The LSQ dataset can again provide a sequence of real-world queries for benchmarking caching systems in realistic settings.

UC4 Usability Aside from efficiency, a crucial aspect of SPARQL research and development is to explore techniques that allow non-expert users to express queries against endpoints more easily. A number of techniques have been proposed to enhance the usability of SPARQL endpoints, including works on auto-completion [25,52,73], query relaxation [38,43,96] and query builders [10,27,44,95]. Such works could use the LSQ dataset to investigate patterns in how users iteratively formulate more complex queries, causes for queries with empty results, as well as to detect the most important features that interfaces must support.

UC5 Optimisation Understanding the most common cases encountered in real-world queries can allow for optimising implementations towards those cases. One such optimisation is to define workload-aware schemes for local [8,9] and distributed [4,28,45] indexing that attempt to group data commonly requested together in the same region of storage; other optimisations look at scheduling the execution of parallel query requests in an effective and fair manner [56], or propose efficient algorithms for frequently encountered patterns in queries [58]. The LSQ dataset can provide diverse examples of real workloads to help configure and evaluate such techniques.

UC6 Meta-Querying The final use case is admittedly more speculative. By meta-querying, we refer to LSQ being used to query for queries of interest, for example, to find the (most common) queries that are asked about specific resources, such as finding out what queries are being asked involving `dbr:Zika_virus`, or what frequent co-occurrences of resources appear in queries. Meta-querying along these lines may help to understand what are the common information needs of users.

These six use cases are intended to help motivate the dataset, to give ideas of potential applications, and also to help distil some key requirements for the design of the dataset. The list should not be considered complete, as other use cases will naturally arise in future. We identify the following facets of the dataset as relevant to support the aforementioned six use cases.

F1 Static Query Features LSQ should describe the key features of each query independently of the dataset. These include SPARQL keywords (e.g., `UNION`, `DISTINCT`), syntactic features (e.g., property paths), and structural features (e.g., multi-way joins, number of projected variables, statistics relating to basic graph patterns (BGPs), etc.). Furthermore, the query should make the resources it mentions explicit. Static features are of key importance to **UC1**, **UC2**, **UC4**, **UC5** and **UC6**.

F2 Provenance LSQ should provide provenance meta-data about the execution of each query, including the endpoint it was issued to, a timestamp of when it was executed, and an anonymised identifier for the client. Timestamps are of particular importance to **UC3** and **UC4**, while an anonymised identifier for the client is mostly of importance to **UC4**.

F3 Runtime Query Statistics LSQ should include statistics of the evaluation of the query over the original dataset, including the number of results returned, the estimated runtime, and the selectivity of individual patterns in the query. Again, making such statistics available allows clients to select and analyse queries with regard to these features without having to execute them over the original dataset. Runtime statistics are of particular importance to **UC1**, **UC3**, **UC4** and **UC5**.

These facets guide the design of the LSQ dataset in terms of what is included, and how the descriptions of individual queries are represented in RDF.

3. Data model & vocabulary

In this section, we describe the data model and vocabulary employed by LSQ for describing SPARQL queries. First, we identify a number of desiderata:

D1 Generality The data model should facilitate a variety of use cases and cover at least the aforementioned facets (**F1**–**F3**) without the need for clients to parse the raw query strings.

D2 Conciseness With logs containing millions of queries, the data model should be relatively concise – in terms of triples produced per query – to keep LSQ at a manageable volume of data.

D3 Usability Core competency questions over the dataset (e.g., find all queries using a particular feature) should be expressible in terms of simple queries that are efficient to evaluate.

D4 Linked Data Compatibility URIs should be dereferenceable so as to abide by the Linked Data Principles. Terms from external well-known vocabularies should be re-used where appropriate. Links to other datasets should be provided.

It is important to note that some of these desiderata are incompatible. For example, **D2** is in direct conflict with **D1** as adding more meta-data for queries can increase generality, but decreases conciseness. **D2** can also be seen as being in conflict with **D3** and **D4**, as **D3** can be achieved by adding "shortcut" representations for common needs, while **D4** requires the addition of links to external datasets, both of which reduce conciseness. Consequently, the data model must find a balance between providing a detailed description of each query, being useful for various purposes, and keeping the overall dataset relatively concise and manageable.

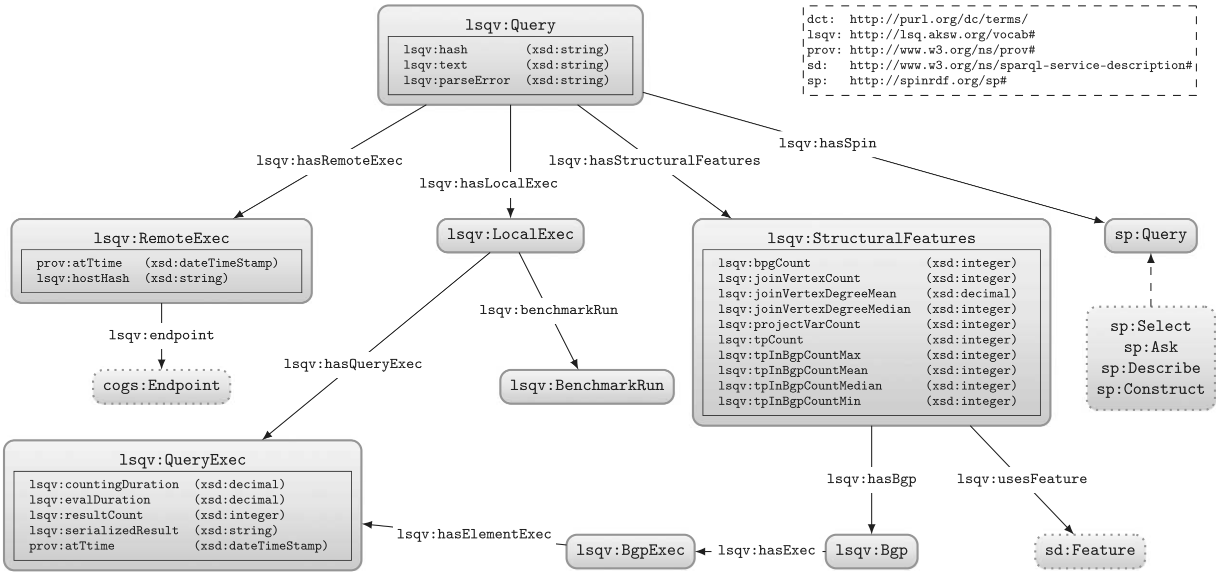


Fig. 1. Core of the LSQ data model: dashed lines indicate sub-classes; datatype properties are embedded within their associated class nodes to simplify presentation; external classes are shown with dotted borders. For clarity, we do not show details of the SPIN representation, or the execution of query elements more fine-grained than BGPs (which follow a similar pattern).

In Fig. 1 we provide an overview of the model used to represent queries in RDF, while in Listing 1 we provide a snippet of the top-level data generated for a query found in the SWDF logs.[3] We now discuss the groups of features described for each query.

Query instance We define a "query" to be uniquely identified by the syntactic query string (independently of the endpoint, the particular execution, etc.). We type these queries with `lsqv:Query`. Instances of this class are linked to the query string using `lsqv:text`, and to various instances of local and remote executions. Other links are provided to other resources that capture further details of the static features of the query, its structure, as well as runtime statistics of its local execution (on our server) as information about its remote execution (on the original server).

Static features Next we define some static features of the query, independent of the dataset over which it is evaluated. These include links to its individual join variables, triple patterns, and basic graph patterns; the SPARQL features that is uses; its number of projected variables, basic graph patterns, join variables, triple patterns; the maximum, mean and median degree of its join variables; and the maximum and minimum size of its basic graph patterns. The triple patterns and basic graph patterns themselves link to the SPIN representation of the query included in the description (and discussed presently); the triple patterns, in turn, link to the resources used by the query. The join variables, on the other hand, are described separately, indicating the degree of the variable and type of join [81] it induces.

SPIN representation While the static features aim to capture some high-level descriptions of the query that may be of interest to specific use cases, some details may be missing. In the interest of generality, we also include for each query a SPARQL Inferencing Notation (SPIN) [48] representation of the query, which essentially captures a fine-grained translation of the SPARQL query to RDF. This SPIN encoding can be translated back to a SPARQL query equivalent to the original.[4]

[3]Note that for the purposes of presentation, we abbreviate some of the details of the query, including the IRIs used to identify local query executions.

[4]Given a query Q and dataset D, let $Q(D)$ denote the result(s) of evaluating Q over D. Two queries Q_1 and Q_2 are then defined to be *equivalent* if and only if $Q_1(D) = Q_2(D)$ for every dataset D.

```
@prefix rdf:  <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix lsqr: <http://lsq.aksw.org/> .
@prefix lsqv: <http://lsq.aksw.org/vocab#> .
@prefix rdfs: <http://www.w3.org/2000/01/rdf-schema#> .
@prefix swc:  <http://data.semanticweb.org/ns/swc/ontology#> .
@prefix swr:  <http://data.semanticweb.org/> .
@prefix xsd:  <http://www.w3.org/2001/XMLSchema#> .
@prefix prov: <http://www.w3.org/ns/prov#> .

# Primary resource describing the query found with the SWDF logs
lsqr:lsqQuery-3wBd2uKotB_-vUxnngs6ZNsGPhJmIDD9c7ig0UI24y8
  lsqv:hasLocalExec lsqr:localExec-v9fBp3ElS1aVXXN1Z8zX1jxcHX3iy-axTgRrU2c7NY8 ;
  lsqv:hasRemoteExec lsqr:re-data.semanticweb.org-sparql_2014-05-22T16:08:17Z ,
    lsqr:re-data.semanticweb.org-sparql_2014-05-20T13:24:13Z ;
  lsqv:hasStructuralFeatures lsqr:lsqQuery-3wBd2uKotB_-vUxnngs6ZNsGPhJmIDD9c7ig0UI24y8-sf ;
  lsqv:hash "3wBd2uKotB_-vUxnngs6ZNsGPhJmIDD9c7ig0UI24y8" ;
  lsqv:text """PREFIX  rdf:  <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
                 PREFIX  swc:  <http://data.semanticweb.org/ns/swc/ontology#>
                 SELECT DISTINCT  ?prop
                 WHERE { ?obj  rdf:type swc:SessionEvent ; ?prop ?targetObj FILTER isLiteral(?targetObj)  }
                 LIMIT   150""" .

# Static features of the query
lsqr:lsqQuery-3wBd2uKotB_-vUxnngs6ZNsGPhJmIDD9c7ig0UI24y8-sf
  lsqv:bgpCount 1 ;
  lsqv:hasBgp lsqr:bgp-_x9Mckke-V9R3ddISuw-Nj_j278nT5HwiA1WUNk7tgY ;
  lsqv:joinVertexCount 1 ;
  lsqv:joinVertexDegreeMean 2 ;
  lsqv:joinVertexDegreeMedian 2 ;
  lsqv:projectVarCount 1 ;
  lsqv:tpCount 2 ;
  lsqv:tpInBgpCountMax 2 ;
  lsqv:tpInBgpCountMean 2 ;
  lsqv:tpInBgpCountMedian 2 ;
  lsqv:tpInBgpCountMin 2 ;
  lsqv:usesFeature lsqv:fn-isLiteral , lsqv:Select , lsqv:Limit , lsqv:Functions , lsqv:Group , lsqv:Filter ,
    lsqv:Distinct , lsqv:TriplePattern .

# Remote execution no. 1 on the original endpoint
lsqr:re-data.semanticweb.org-sparql_2014-05-22T16:08:17Z
  prov:atTime "2014-05-22T16:08:17Z"^^xsd:dateTime ;
  lsqv:endpoint swr:sparql ;
  lsqv:hostHash "O5UQpDtofxAsrJk7yzGfDolFGylMFw5446KcRZDcBkU" .

# Remote execution no. 2 on the original endpoint
lsqr:re-data.semanticweb.org-sparql_2014-05-20T13:24:13Z
  prov:atTime "2014-05-20T13:24:13Z"^^xsd:dateTime ;
  lsqv:endpoint swr:sparql ;
  lsqv:hostHash "7aPNvqsgizRuEjH7_cO_dXoqLk-exKJ-xFmbCH3ew_E" .

# Local execution to extract statistics
lsqr:localExec-v9fBp3ElS1aVXXN1Z8zX1jxcHX3iy-axTgRrU2c7NY8-xc
  lsqv:benchmarkRun lsqr:xc-swdf_2020-09-23_at_23-09-2020_17:10:19 ;
  lsqv:hasQueryExec lsqr:queryExec-Cmv7SccybbBxwkep_cHvDiF3piq29tH7NWlDfIiCHqU .

# Results of local execution
lsqr:queryExec-Cmv7SccybbBxwkep_cHvDiF3piq29tH7NWlDfIiCHqU
  prov:atTime "2020-09-23T15:27:36.325Z"^^xsd:dateTime ;
  lsqv:countingDuration 0.008466651 ;
  lsqv:evalDuration 0.008868635 ;
  lsqv:resultCount 16 .

# The full data further include a SPIN description of the query, a list of BGPs within the query,
# a list of triple patterns and terms within the query, as well as execution statistics for individal
# BGPs, triple patterns and sub-BGPs induced by join variables
```

Listing 1. An example LSQ/RDF representation of a SPARQL query in Turtle syntax

Remote execution(s) Next, individual queries are associated with one or more executions on the original endpoint, including a timestamp of when the query was executed, as well as an anonymised ID for the client – based on their cryptographically-hashed and salted I.P. – to identify which queries are run by the same agent.[5] The remote execution is also linked to the originating endpoint using `lsqv:endpoint`.[6] Given that these meta-data constitute provenance for the query, we use the PROV Ontology (PROV-O) [51] for modelling the time, date and agent involved in the remote execution.

Local execution In most cases, the log of the remote executions will not provide statistics about the execution of the query in terms of how many results were returned, how long it took, how selective were the individual patterns, and so forth. Hence we re-execute the queries offline against the original dataset to generate runtime statistics about the query. Local executions were run on a machine with 64 core Intel(R) Xeon(R) CPU E5-2683 v4 @ 2.10 GHz, and 528 GB RAM running Ubuntu 18.04.5 LTS using Virtuoso 7.2.[7] Due to the large number of queries to evaluate, we set a query timeout of one minute. The statistics generated include the number of results and the runtime for the query, as well as the number of results and the selectivity for each individual triple pattern.[8] Runtime statistics are computed in a controlled environment that abstract away external factors such as the load on the endpoint server, etc.; however, due to the costs involved in evaluating such queries, we compute these only for one query engine, namely Virtuoso 7.2, where runtime estimates may thus vary for other engines.

Summary The meta-data described in this section aim to strike a balance in terms of the four desiderata mentioned previously. In terms of **Generality**, we provide detailed meta-data for static query features, for provenance, and for runtime query statistics. In terms of **Conciseness**, though the detailed meta-data do require potentially many triples to be encoded for each query, we take steps to reduce this number by re-using resources insofar as appropriate where, for example, each unique query string is encoded once per log, with one set of static features, one SPIN representation, and one set of local executions, being subsequently linked to its different remote executions (rather than duplicate the former meta-data each time the same query string appears in the log). In terms of **Usability**, we provide some "shortcut triples" that allow for quickly finding queries of interest; for example, the static features of the query are largely of this form, where all such meta-data could in principle be computed from the SPIN representation, but using rather complex SPARQL queries over LSQ; the static query features are thus presented to make it easier to find queries, for example, with a certain range of numbers of triple patterns, or queries using `DISTINCT` and `GROUP BY`, etc. We will discuss **Linked Data Compatibility** in the section that follows.

4. Publication

The LSQ dataset is published as Linked Data. Before describing the current contents of LSQ, we discuss in more detail how LSQ has been published.

[5] A "salt" in cryptography is a privately-held arbitrary string that is combined (e.g., concatenated) with the input being hashed in order to avoid attacks based on precomputed tables (e.g., of common values or, in this case, of a collection of I.P.'s of interest).

[6] Although there exist properties called "endpoint" – such as `void:sparqlEndpoint` or `sd:endpoint` – the domains of these properties were not query executions, but rather VoID datasets (i.e., sets of RDF triples), or SPARQL services. Though it would be possible to define properties such as `lsqv:dataset` or `lsqv:service` and then link a query execution `<x>` to an endpoint URL `<e>` with `<x> lsqv:dataset [void:sparqlEndpoint <e>]`, or alternatively `<x> lsqv:service [sd:endpoint <e>]`, this would introduce $O(n)$ additional triples to the LSQ 2.0 dataset, for n the number of remote query executions (in LSQ 2.0, $n = 43{,}952{,}379$). (Please note that the dataset or service may change during the lifetime of the log, which we do not have information about; hence we cannot refer to one dataset/service at a given endpoint.) Thus we rather introduce `lsqv:endpoint` in the data and define property chain axioms in the LSQ 2.0 vocabulary to relate `lsqv:endpoint` to `lsqv:dataset/void:sparqlEndpoint` and `lsqv:service/sd:endpoint`.

[7] The configuration used for Virtuoso was `MaxQueryMem = 32G`, `NumberOfBuffers = 20050000`, and `MaxDirtyBuffers = 20000000`.

[8] The selectivity of the triple pattern is the ratio of triples from the dataset that it selects.

Table 1

Locations from which LSQ can be accessed including an example Linked Data IRI, the vocabulary, dumps, the SPARQL endpoint, as well as locations where LSQ is indexed, including DataHub, Linked Open Vocabularies (LOV) and prefix.cc

Method	Location
Linked Data IRIs	http://lsq.aksw.org/lsqQuery-3wBd2uKotB_-vUxnngs6ZNsGPhJmIDD9c7ig0UI24y8 (*example*)
Vocabulary	http://lsq.aksw.org/vocab
Dumps	http://lsq.aksw.org/downloads
SPARQL Endpoint	http://lsq.aksw.org/sparql
Catalogue	**Location**
Datahub	https://datahub.io/dataset/lsq
LOV	https://lov.linkeddata.es/dataset/lov/vocabs/lsq
prefix.cc	http://prefix.cc/lsqv

Access methods We provide a number of ways to access LSQ. Firstly, following Linked Data principles, all IRIs under the `lsqr:` namespace are made dereferenceable using a `303 Redirect`; this is implemented with LodView[9] and supports content negotiation. A SPARQL endpoint is provided for querying LSQ 2.0. Table 1 lists the locations for these access methods.

Vocabulary As seen in Fig. 1, we use a mixture of a custom vocabulary in the `lsqv:` namespace, as well as existing vocabulary where possible. The custom LSQ vocabulary dereferences (via `303 Redirect`) to an RDFS/OWL definition of the corresponding terms in Turtle, which includes metadata about authors. The vocabulary meets four of the five stars of Linked Data vocabulary use [46].[10] With respect to external vocabulary, we re-use terms from the SPARQL Inferencing Notation (SPIN) ontology [48], as well as the Provenance Ontology (PROV-O) [51] where possible.

Discoverability The LSQ dataset has been registered in the DataHub catalogue, while the LSQ vocabulary has been listed on Linked Open Vocabularies (LOV) [92] as well as prefix.cc. We provide these locations in Table 1. We also compute and publish meta-data about the LSQ dataset using the Vocabulary of Interlinked Datasets (VoID) [5]. More specifically, we compute a separate VoID description for each log and make the resulting description accessible via both a downloadable file and a named graph of the SPARQL endpoint.

Availability The LSQ dataset has been hosted for over six years (at the time of writing) by the Agile Knowledge Engineering and Semantic Web (AKSW) group. As discussed in Section 7, it has been widely adopted in that time. The dataset is available to all under a CC-BY license. We further make the source code used for generating the LSQ dataset from the raw query logs available on Github https://github.com/AKSW/LSQ.

5. LSQ 2.0 logs

We now describe the content of the LSQ 2.0 dataset. In order to collect raw SPARQL query logs, we sent mails both to the `public-lod@w3.org` mailing list and to individual providers of endpoints. We also incorporated logs from LSQ 1.0 [77] and a sample of queries from the Wikidata logs [57]. We thus acquired access to the logs of 27 endpoints, 22 of which are part of Bio2RDF release 3 [33].[11] Table 2 provides high-level statistics of the query logs from which we extract the LSQ dataset, including the query executions registered; the unique query strings; the number of queries providing a runtime error, or returning zero results; as well as the percentage of unique queries using `SELECT`, `CONSTRUCT`, `DESCRIBE` or `ASK`. Aside from the initial log of LSQ, only one log is already publicly available, namely Wikidata [57], of which we include a subset described in our data model.

[9] https://github.com/LodLive/LodView

[10] With respect to the fifth star, which requires that our LSQ vocabulary be *linked to* from external vocabularies, we are not aware of such links, though we do know, for example, that Varga et al. [94] incorporate elements of the LSQ vocabulary within their own Analytical Metadata (AM) model, while Singh et al. [86] also use the LSQ vocabulary within their benchmark.

[11] We also acquired logs for the British Museum and UniProt endpoints, but decided to omit them due to having few unique queries.

Table 2

High-level statistics for queries in the LSQ dataset (QE = Query Executions, UQ = Unique Queries, RE = Runtime Error, ZR = Zero Results, SEL = SELECT, CON = CONSTRUCT, DES = DESCRIBE)

DATASET	QE	UQ	RE	ZR	SEL (%)	CON (%)	DES (%)	ASK (%)
AFFYMETRIX	1,229,339	311,096	277,983	31,659	16.47	83.21	0.02	0.30
BIOMODELS	1,238,375	435,232	412,984	21,692	41.18	58.75	0.00	0.06
BIOPORTAL	1,337,804	89,664	85,273	3,389	64.88	34.78	0.00	0.34
CTD	940,390	287,296	266,999	19,824	11.98	87.76	0.00	0.26
DBPEDIA	6,535,500	4,258,941	1,259,972	1,755,338	69.90	3.59	25.23	1.28
DBSNP	794,023	269,498	267,662	1,698	4.99	94.99	0.00	0.02
DRUGBANK	1,613,951	379,233	372,022	6,186	46.67	52.80	0.05	0.48
GENAGE	589,211	265,067	263,205	1,661	5.55	94.43	0.00	0.02
GENDR	690,864	270,697	262,776	7,726	7.53	92.45	0.00	0.02
GO	1,839,991	121,542	88,743	30,082	98.31	0.03	0.35	1.31
GOA	3,544,273	343,836	310,800	32,317	26.18	73.69	0.06	0.07
HGNC	1,529,681	364,961	327,540	33,568	29.15	70.58	0.04	0.23
IREFINDEX	1,560,704	309,777	289,546	19,858	18.10	81.88	0.00	0.02
KEGG	66,830	19,871	10,386	8,004	92.04	4.30	0.41	3.24
LINKEDGEODATA	154,884	61,897	11,028	13,990	98.58	1.00	0.02	0.40
LINKEDSQP	337,001	204,112	203,534	310	0.28	99.69	0.00	0.03
MGI	1,316,673	319,627	277,080	33,781	21.12	78.60	0.05	0.23
NCBIGENE	770,716	216,832	215,938	718	8.71	91.26	0.00	0.04
OMIM	1,506,621	335,541	290,483	44,093	22.78	76.89	0.08	0.26
PHARMGKB	94,540	24,000	14,597	8,649	60.35	39.65	0.00	0.01
SABIORK	922,407	274,098	253,733	19,938	7.91	92.07	0.00	0.02
SGD	973,281	318,641	309,593	7,199	16.06	80.53	0.30	3.12
SIDER	599,285	277,766	274,963	1,965	9.38	90.59	0.00	0.03
SWDF	1,415,567	101,423	30,792	36,789	73.57	0.06	26.17	0.21
TAXONOMY	7,698,898	354,582	334,290	20,041	15.83	84.16	0.00	0.02
WIKIDATA	3,298,254	844,256	520,976	150,395	95.03	0.13	0.08	4.77
WORMBASE	1,353,316	498,170	496,325	1,660	49.33	50.66	0.00	0.01
Overall	43,952,379	11,557,656	7,729,223	2,312,530	36.14	57.8	1.89	0.60

AFFYMETRIX is a biomedical Linked Dataset describing probesets found in DNA microarrays [33].
BIOMODELS is a biomedical Linked Dataset describing mathematical models of biological systems [33].[12]
BioPortal is a biomedical Linked Dataset cataloguing biomedical ontologies [33].
CTD: Comparative Toxicogenomics Database is a biomedical Linked Dataset that describes how environmental chemicals relate to diseases [33].
DBPEDIA is a cross-domain Linked Dataset that is primarily extracted from Wikipedia [53].
DBSNP: Single Nucleotide Polymorphism Database is a biomedical Linked Dataset that describes single base nucleotide substitutions and short deletion and insertion polymorphisms [33].
DRUGBANK is a biomedical Linked Dataset that describes drugs and drug targets [33].
GENAGE is a biomedical Linked Dataset that describes human and other genes linked with ageing [33].
GENDR: Dietary Restriction Gene Database is a biomedical Linked Dataset that describes genes associated with dietary restrictions [33].
GO: Gene Ontology is a biomedical ontology that describes gene, gene products, and their functions [33].
GOA: Gene Ontology Annotation is a biomedical Linked Dataset that provides annotations on proteins, RNA and protein complexes [33].

[12]The external SPARQL endpoint is spelt `biomedels`, and thus the IRIs use this spelling in LSQ 2.0.

HGNC: HUGO Gene Nomenclature Committee is a biomedical Linked Dataset that describes human gene nomenclature [33].

IREFINDEX is a biomedical Linked Dataset that indexes interaction data for proteins [33].

KEGG: Kyoto Encyclopedia of Genes and Genomes is a biomedical Linked Dataset that describes functions of genes and biological systems [33].

LINKEDGEODATA is a geographical Linked Data extracted primarily from Open Street Map [88].

LINKEDSQP: Linked Structured Product Labelling is a biomedical Linked Dataset that contains meta-data about drug labels sourced from DailyMed [33].

MGI: Mouse Genome Informatics is a biomedical Linked Dataset that describes mouse genes, alleles, and strains [33].

NCBI Gene is a biomedical Linked Dataset that describes gene-related information given by the National Center for Biotechnology Information (NCBI) [33].

Online Mendelian Inheritance in Man (OMIM) is a biomedical Linked Dataset that catalogues human genes as well as genetic traits and disorders [33].

PHARMGKB is a biomedical Linked Dataset describing how genetic variations impact drug responses [33].

SABIORK: System for the Analysis of Biochemical Pathways – Reaction Kinetics is a biomedical Linked Dataset that describes biochemical reactions [33].

SGD: Saccharomyces Genome Database is a biomedical Linked Dataset describing the biology and genetics of the yeast *Saccharomyces cerevisiae* [33].

SIDER: Side Effect Resource is a biomedical Linked Dataset describing the side effects of drugs [33].

SWDF: Semantic Web Dog Food is a bibliographical Linked Dataset describing papers, presentations and people participating in top Semantic Web related conferences and workshops [61].

TAXONOMY: NBCI Taxonomy is a biomedical Linked Dataset that describes all organisms found in genetic databases [33].

WIKIDATA is a collaboratively edited knowledge graph hosted by the Wikimedia foundation [57].

WORMBASE is a biomedical Linked Dataset that describes the biology and genome of worms [33].

6. LSQ 2.0 query statistics

We now look in more detail at the composition of the queries currently included in the LSQ dataset. In particular, we first look at some high-level statistics for queries in the dataset, before looking at the static features of the query, the agents making the queries, as well as runtime statistics computed against the corresponding dataset. Finally we discuss the composition of the LSQ dataset itself.

High-level statistics Table 2 provides a high-level analysis of the queries (both query executions and unique queries) appearing in each of the logs considered. From the overall row, we see that LSQ contains 43.95 million query executions and 11.56 million unique queries, implying that each query is executed, on average, 3.8 times within each log. Of the unique queries, 7.7 million (66.9%) have runtime errors; and 2.3 million (20.0%) have no errors but return empty results. A high ratio of runtime errors come from the Bio2RDF logs. The majority of queries are `CONSTRUCT` queries (60.0%), followed by `SELECT` (32.3%), `DESCRIBE` (7.1%) and `ASK` (0.5%). We find that `CONSTRUCT` queries are particularly prevalent on Bio2RDF endpoints, while `DESCRIBE` queries are particularly prevalent on DBPEDIA and Wikdata endpoints, possibly due to the use of such queries for dereferencing Linked Data IRIs through the endpoint.

Static features Turning to static features, we first look at the percentages of unique queries without parse errors using different SPARQL features (note that we will analyse joins in BGPs and property paths later). Table 3 provides statistics for the usage of different features of SPARQL. We see that `FILTER` is among the most widely used features, along with SPARQL functions and expressions (note that almost all filters use such expressions). This feature is followed by `DISTINCT` and other solution modifiers, `UNION`, `OPTIONAL`, etc. Notably these are all SPARQL 1.0 features. The `SERVICE` keyword is commonly used on WIKIDATA since the Wikidata Query Service provides a custom service for retrieving multilingual labels as preferred/available.

Table 3

Percentage of unique queries without parse errors using the specified SPARQL feature (SOL. MOD. includes the solution modifiers `ORDER BY`, `OFFSET`, and `LIMIT`; AGG. includes aggregation features `GROUP BY`, `HAVING`, `AVG`, `SUM`, `COUNT`, `MAX`, and `MIN`; NEG. includes `MINUS`, `NOT EXISTS`, and `EXISTS`; BIND. includes `VALUES` and `BINDING`; GRAPH includes `FROM`, `FROM NAMED`, and `GRAPH`; FUNC. includes SPARQL functions and expressions)

DATASET	UNION	OPTIONAL	DISTINCT	FILTER	REGEX	SERVICE	SUB-Q.	SOL. M.	AGG.	NEG.	BIND.	GRAPH	FUNC.
AFFYMETRIX	3.68	0.02	7.64	83.30	0.15	0.01	0.06	4.85	0.36	0.00	0.01	0.69	83.30
BIOMODELS	2.64	0.01	0.18	94.32	0.06	0.00	0.01	0.12	0.10	0.00	0.00	0.03	94.32
BIOPORTAL	1.50	0.06	0.05	37.95	2.23	0.01	0.01	0.21	34.10	0.00	0.00	34.26	37.95
CTD	3.99	0.02	0.37	88.06	0.06	0.04	0.01	3.57	0.13	0.00	0.01	3.21	88.06
DBPEDIA	28.68	19.97	22.22	29.87	4.10	0.00	2.22	8.92	9.98	0.00	1.11	0.01	29.87
DBSNP	0.05	0.01	0.10	94.87	0.00	0.05	0.01	0.13	0.07	0.00	0.00	0.09	94.87
DRUGBANK	2.58	15.55	12.37	54.67	1.81	0.10	0.02	9.31	2.59	0.00	0.01	2.73	54.67
GENAGE	0.00	0.01	0.08	94.37	0.00	0.00	0.01	0.06	0.07	0.00	0.00	0.02	94.37
GENDR	0.01	0.01	0.07	96.55	0.00	0.01	0.01	0.06	0.07	0.00	0.00	0.02	96.55
GO	9.08	0.16	20.98	18.82	5.92	0.89	0.07	3.86	0.08	0.00	0.01	0.02	18.82
GOA	4.17	0.01	5.00	84.76	9.15	0.86	0.03	0.71	0.09	0.00	0.00	0.44	84.76
HGNC	3.16	0.02	5.00	84.12	0.04	0.03	0.02	1.20	0.44	0.00	0.00	0.47	84.12
IREFINDEX	9.99	1.00	0.86	83.37	2.29	0.01	0.01	0.87	0.12	0.00	0.00	0.74	83.37
KEGG	11.64	1.13	54.91	7.22	2.86	0.07	0.04	42.95	1.02	0.00	0.01	0.79	7.22
LINKEDGEODATA	1.15	19.13	9.24	18.06	2.61	0.01	7.64	30.75	37.57	0.00	0.52	2.52	18.06
LINKEDSQP	0.00	0.01	0.00	99.76	0.00	0.00	0.01	0.05	0.07	0.00	0.00	0.03	99.76
MGI	3.57	0.02	6.99	79.43	0.43	0.01	0.03	2.98	0.57	0.00	0.05	0.64	79.43
NCBIGENE	0.02	0.01	0.17	91.53	0.02	0.03	0.01	2.72	0.22	0.00	0.00	2.61	91.53
OMIM	3.52	1.10	4.90	80.83	0.31	0.39	0.04	5.62	0.93	0.00	0.01	1.09	80.83
PHARMGKB	33.05	0.00	42.22	47.92	0.28	0.13	0.01	43.40	0.07	0.00	0.00	1.14	47.92
SABIORK	4.15	0.01	0.12	92.00	0.00	0.00	0.01	0.17	0.09	0.00	0.00	0.05	92.00
SGD	1.63	0.01	6.73	80.06	0.09	0.03	0.04	4.38	3.87	0.00	0.00	4.24	80.06
SIDER	0.02	0.01	7.44	90.87	0.00	0.03	0.01	7.42	0.09	0.00	0.00	0.73	90.87
SWDF	40.13	34.08	53.16	2.34	0.87	0.04	0.10	31.45	1.08	0.00	0.01	32.32	2.34
TAXONOMY	3.19	0.01	0.04	92.91	0.04	0.00	0.01	0.35	0.25	0.00	0.00	0.44	92.91
WIKIDATA	9.27	29.21	15.32	26.48	1.13	54.38	7.44	40.72	7.99	0.00	8.99	0.00	26.48
WORMBASE	14.16	4.46	0.12	69.92	9.69	1.58	0.00	0.27	0.63	0.00	0.00	0.82	69.92
Overall	7.22	4.67	10.23	67.57	1.63	2.17	0.66	9.14	3.77	0.00	0.34	3.34	67.57

Next, in Table 4, we provide three types of statistics about the basic graph patterns and property path features used. First, we present the unique number of subject, predicate and object terms used in the BGPs of the logs in order to characterise their diversity. We see that DBPEDIA, LINKEDGEODATA and WIKIDATA offer the most diversity, particularly in terms of predicates found in the queries. Second, we present the percentage of queries with different types of joins in the basic graph patterns [81]. Each join variable in a basic graph pattern is analysed in order to understand how they connect triple patterns. We say that a join vertex has an "outgoing link" if it appears as a subject of a triple pattern, and that it has an "incoming link" if it appears as predicate or object. The join types are then defined as follows:

STAR has multiple outgoing but no incoming links.
PATH has one incoming and one outgoing link.
HYBRID has at least one incoming and outgoing link and three or more links overall.
SINK has multiple incoming but no outgoing links.

From Table 4, we see that the majority of queries have no joins, but where present, STAR joins are the most frequent, followed by HYBRID and SINK joins. Third, we present the number of queries using different property path features, where we see that DBPEDIA and WIKIDATA contain the most use of property path queries, while Bio2RDF logs exhibit little use of this feature. The most used such feature is/for concatenation.

These statistics may be helpful for consumers to choose which dataset/log to work with. For example, for the purposes of benchmarking joins, a dataset such as LINKEDGEODATA or WIKIDATA may be chosen as most queries feature joins; in order to benchmark or analyse property paths, DBPEDIA or WIKIDATA may be chosen as they use this feature more frequently; etc.

Provenance: Executions and agents Next we look at how many clients (anonymised IPs) and unique queries underlie the executions registered in order to compare the diversity of the different datasets. Note that client information is not available for WIKIDATA. In Fig. 2(a) and Fig. 2(b), we present Lorenz curves for the number of executions per client and per query, respectively.[13] We present results for Bio2RDF together as one series to ensure better readability. In general, we see a skew in the graph away from the equality curve towards the bottom-left corner, meaning that a small number of clients/queries are involved in a large number of executions. The skew is more evident in the case of clients, and particularly for the SWDF and Bio2RDF datasets; thus consumers of LSQ 2.0 should be aware that a high ratio of queries from these datasets come from a small number of clients (likely bots). DBPEDIA is the most diverse in terms of clients and queries.

Static and runtime statistics Next, in order to characterise how complex the queries are to evaluate, in Table 5 we present some relevant static and runtime statistics, where static statistics can be computed from the query string, while runtime statistics require evaluating the query locally (only queries that were successfully run are counted; see Table 2 for statistics on runtime errors). Regarding runtimes, we recall that these were run with a one minute timeout, which represents the max runtime. We see that LINKEDGEODATA contains the most costly queries to run, which appears to correlate with larger result sizes and a larger mean join-vertex degree. Relatively high runtimes are also seen for the KEGG dataset. The simplest queries to run are found in the GENAGE, GENDR and TAXONOMY datasets. These results suggest, for example, that LINKEDGEODATA might be more suitable for consumers looking for a challenging benchmark.

LSQ dataset statistics The LSQ 2.0 dataset, describing 43.95 million executions of 11.56 million unique queries, contains 1.24 billion triples, split into 27 named graphs (one for each of the datasets listed).[14]

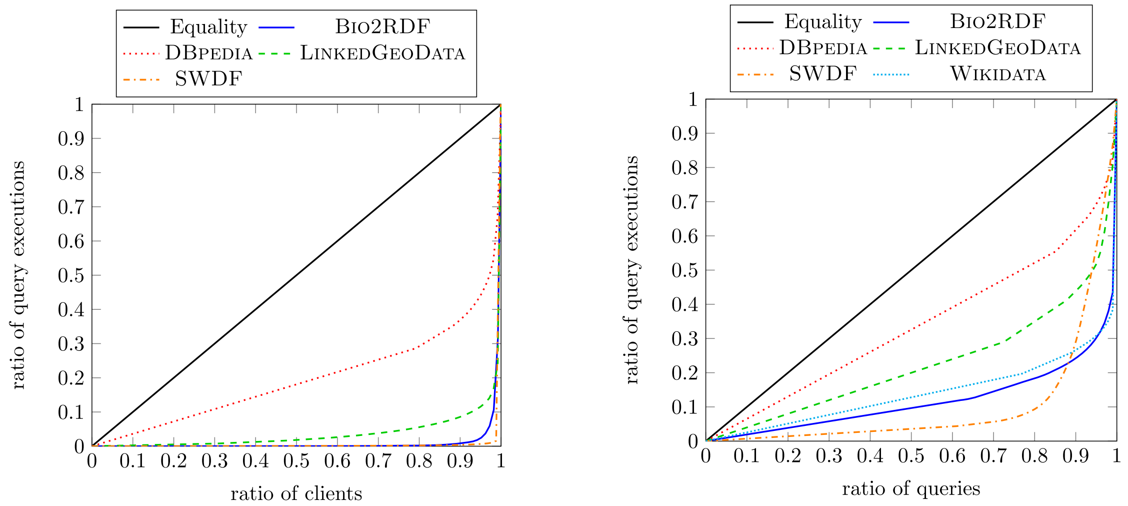
[13]Lorenz curves visualise (in)equality in distributions for a given quantity over a given set of elements: a coordinate (x, y) indicates that ratio x of elements (given in ascending order by their quantity) are associated with ratio y of the total quantity. The solid black line indicates a hypothetical equality where each element is associated with the same quality. For example, in Fig. 2(a) on the DBPEDIA curve, the point (0.80, 0.29) denotes that 80% of clients invoke 29% of the executions (or 20% of the clients invoke 71% of the executions).

[14]We exclude some named graphs created by Virtuoso.

Table 4

Analysis of basic graph patterns and property paths including number of unique subject/predicate/object terms, percentage of unique queries containing different types of joins (a query may contain multiple join types), and number of queries using different types of property path expressions (/ denotes concatenation, ^ denotes inverse, * denotes zero-or-more; + denotes one-or-more; | denotes disjunction

Dataset	BGP Terms			Join Types (%)					Prop. Path Features				
	Subj.	Pred.	Obj.	Star	Hyb.	Path	Sink	None	/	^	*	+	|
Affymetrix	17,912	432	27,398	2.36	0.16	0.03	0.10	97.57	2	0	0	0	1
BioModels	14,055	347	120,148	37.22	0.10	0.01	0.04	62.71	2	0	0	0	1
BIOPORTAL	9,275	130	6,275	36.26	34.22	0.01	53.08	44.60	1	0	0	0	1
CTD	14,927	276	22,320	1.72	0.19	0.04	0.16	98.21	3	1	0	0	1
DBpedia	912,943	10,842	1,104,732	29.38	7.06	1.71	15.48	69.56	49,660	39,039	271	7,582	32,709
dbSNP	12,825	112	6,069	2.10	0.06	0.01	0.04	97.86	2	0	0	0	1
DrugBank	37,578	989	34,601	33.39	16.81	2.01	7.50	64.44	8	0	1	0	1
GenAge	2,666	113	11,875	4.30	0.04	0.01	0.01	95.66	2	0	0	0	1
GenDR	5,664	104	705	4.22	4.17	0.01	0.01	95.74	3	0	0	0	1
GO	35,504	394	59,362	16.51	0.90	0.87	1.31	83.14	4	2	0	0	1
GOA	33,593	204	22,044	8.06	0.05	0.02	0.02	91.89	5	0	0	0	1
HGNC	23,430	414	36,857	15.72	1.53	0.02	4.30	84.21	2	0	0	0	1
iRefIndex	20,067	171	28,069	9.09	0.35	0.01	1.50	90.85	2	0	0	0	1
KEGG	5,620	251	8,964	7.24	1.67	0.51	0.93	92.08	3	0	0	0	1
LinkedGeoData	13,498	5,991	2,628	49.51	24.15	0.04	34.27	41.28	672	78	0	0	9
LinkedSQP	326	55	144	0.05	0.03	0.02	0.00	99.91	2	0	0	0	1
MGI	28,702	391	23,867	2.13	1.36	0.15	0.56	97.79	5	0	0	0	1
NCBIGene	11,753	254	4,427	2.16	0.20	0.02	0.18	97.79	3	0	1	0	1
OMIM	23,504	623	50,229	7.00	4.57	0.34	3.95	92.52	10	0	0	0	3
PharmGKB	1,099	83	13,548	8.03	50.69	0.82	1.83	47.97	0	0	0	0	1
SABIORK	14,224	156	19,775	0.70	0.04	0.02	0.01	99.25	2	0	0	0	1
SGD	7,228	508	13,460	6.83	5.65	0.03	4.02	93.06	2	0	0	0	1
SIDER	8,792	152	3,589	0.53	0.08	0.02	0.04	99.43	6	0	0	0	1
SWDF	25,640	420	10,823	32.05	7.27	3.34	0.95	58.62	94	22	0	0	17
Taxonomy	16,201	207	97,298	22.54	0.23	0.01	0.21	77.41	6	0	0	0	1
Wikidata	47,871	11,779	263,974	46.63	17.59	4.98	12.05	41.20	134,811	2,944	3,838	0	23,525
Wormbase	53,807	148	24,083	39.40	5.13	4.47	5.07	60.55	2	0	0	0	1
Overall	1,398,704	35,546	2,017,264	15.74	6.58	0.72	5.47	80.56	185,314	42,086	4,111	7,582	56,285



(a) Lorenz curve for distribution of executions per client. (b) Lorenz curve for distribution of executions per query.

Fig. 2. Lorenz curves for the LSQ dataset

7. LSQ adoption

In this section we present how LSQ has been adopted since its initial release with four logs in 2015. We organise this discussion following the motivational use cases we originally envisaged, as presented in Section 2. Table 6 provides an overview of the research works that have used LSQ, and the relevant use case(s) that they target. We now discuss these works in more detail; note that in the case of works that relate to multiple use cases, we will discuss them once in what we identify to be the "primary" related use case. We further discuss some works that have used the LSQ dataset for use cases beyond the six we had originally envisaged.

UC1: Custom Benchmarks LSQ has been adopted in various works for creating custom benchmarks.

- Saleem et al. [79] present a framework for generating benchmarks that can be used to evaluate SPARQL endpoints under typical workloads; the benchmarks generate query types depending on the features of the queries submitted to the endpoint, where LSQ is used for testing.
- Later works by Saleem et al. further propose frameworks for generating benchmarks from LSQ for the purposes of evaluating query containment [80,82] and federated query evaluation [78], as well as comparing existing SPARQL benchmarks against LSQ in order to understand how representative they are of real workloads [83].
- Hernández et al. [42] present an empirical study of the efficiency of graph database engines for answering SPARQL queries over Wikidata; they refer to LSQ to verify that the query shapes considered for evaluation correspond with other analyses of real-world SPARQL queries.
- Fernández et al. [35] evaluate various archiving techniques and querying strategies for RDF archives that store historical data; in their evaluation, they select the 200 most frequent triple patterns from the DBpedia query set in LSQ.
- Azzam et al. [15] use LSQ for retrieving highly-demanding queries from the dataset in order to evaluate their system for dividing the load processed by different SPARQL servers.
- Bigerl et al. [18] develop a tensor-based triple store, where they used LSQ as input to the FEASIBLE framework to generate a custom benchmark.
- Azzam et al. [14] present a system that dynamically delegates query processing load between clients and servers. The authors use the Linked Data Fragments client/server approach improving it with the aforementioned technique and use 16 queries from LSQ to complement their evaluation.

Table 5

Comparison of the mean values of runtime statistics across all query logs (PVs = Project Variables, BGPs = Basic Graph Patterns, TPs = Triple Patterns, JVs = Join Vertices, MJVD = Mean Join Vertex Degree, MTPS = Mean Triple Pattern Selectivity)

Dataset	Static Statistics (mean)					Runtime Statistics (mean)		
	PVs	BGPs	TPs	JVs	MJVD	MTPS	Result Size	Runtime (sec)
Affymetrix	1.93	1.06	1.10	0.03	0.06	0.82	12708.39	0.084
BioModels	1.24	1.04	1.42	0.37	0.75	0.57	4896.67	0.011
BIOPORTAL	1.16	1.03	1.94	1.43	1.12	0.54	1699.48	0.004
CTD	2.56	1.05	1.08	0.02	0.04	0.85	24354.24	0.102
DBpedia	2.78	2.37	3.23	0.93	0.66	0.01	114038.38	0.164
dbSNP	1.09	1.02	1.04	0.02	0.04	0.97	757108.37	0.009
DrugBank	2.61	1.05	1.93	0.69	0.91	0.66	119759.38	0.007
GenAge	1.88	1.00	1.09	0.04	0.13	0.99	1642.84	0.003
GenDR	2.73	1.00	1.08	0.08	0.09	0.97	83.50	0.003
GO	1.46	1.10	1.37	0.22	0.38	0.02	93806.20	0.046
GOA	1.87	1.03	1.12	0.08	0.16	0.85	7692.26	0.016
HGNC	1.91	1.05	1.29	0.23	0.35	0.80	2419.43	0.019
iRefIndex	2.92	1.13	1.43	0.19	0.25	0.82	32200.76	0.077
KEGG	2.27	1.15	1.31	0.13	0.18	0.33	175469.53	3.862
LinkedGeoData	2.27	1.16	2.62	1.10	1.76	0.15	11055973.09	6.788
LinkedSQP	2.01	1.00	1.00	0.00	0.00	1.00	9503.41	0.014
MGI	2.04	1.04	1.11	0.05	0.06	0.84	2050.76	0.178
NCBIGene	1.39	1.02	1.04	0.03	0.04	0.95	10731.33	0.021
OMIM	1.83	1.07	1.26	0.17	0.18	0.77	3505.54	0.020
PharmGKB	1.96	1.34	2.48	1.06	1.08	0.39	255.61	0.017
SABIORK	2.96	1.05	1.06	0.01	0.02	0.88	1610.77	0.005
SGD	1.45	1.12	1.96	0.35	0.18	0.58	108951.60	0.058
SIDER	1.34	1.00	1.01	0.01	0.01	0.98	9703.86	0.010
SWDF	4.04	3.37	3.97	0.45	0.92	0.03	37362.67	0.007
Taxonomy	1.77	1.17	1.53	0.23	0.59	0.69	1928.75	0.004
Wikidata	3.00	2.47	4.73	1.06	1.81	0.00	17817773.63	0.412
WormBase	1.56	1.25	2.05	0.65	0.87	0.98	9888.61	0.007
Overall	2.07	1.26	1.71	0.35	0.47	0.65	1126559.96	0.440

- Davoudian et al. [30] present a system that partitions graphs depending on the access frequency to their nodes. In this way the system implements workload-aware partitioning. The authors use LSQ for evaluating their approach.
- Desouki et al. [32] propose a method to generate synthetic benchmark data. To generate these synthetic data they use other RDF graphs available, such as SWDF and DBpedia 2016. They benchmark their approach using queries from LSQ.
- Röder et al. [74] develop a method to predict the performance of knowledge graph query engines; to do so the authors use a stochastic generation model that is able to generate graphs of arbitrary sizes similar to the input graph. They use LSQ as a benchmark of real-world queries.

UC2: SPARQL adoption Other works have used LSQ to understand how SPARQL is being used in practice.

- Han et al. [41] provide a statistical analysis of the queries of LSQ, surveying both syntactic features, such as the number of triple patterns, the SPARQL features used, the frequency of well-designed patterns; as well as semantic properties, such as montonicity, weak-monotonicity, non-monotonicity and satisfiability.
- Bonifati et al. [21,22] conduct detailed analysis of the queries in various logs, including LSQ; they study a variety of phenomena in these queries, including their shape, their (hyper)treewidth, common abstract patterns

Table 6

Research works making use of the LSQ dataset since its initial release, ordered by year and then alphabetically by author name, with relevant use cases indicated (UC1: Custom Benchmarks; UC2: SPARQL Adoption; UC3: Caching; UC4: Usability; UC5: Optimisation; UC6: Meta-Querying)

NAME	YEAR	UC 1	UC 2	UC 3	UC 4	UC 5	UC 6	Other
Saleem et al. [79]	2015	✓						
Arenas et al. [11]	2016	✓			✓			
Benedetti and Bergamaschi [17]	2016				✓			
Georgala et al. [39]	2016							✓
Han et al. [41]	2016		✓			✓		
Hernandez et al. [42]	2016	✓						
Knuth et al. [49]	2016	✓		✓				
Rico et al. [71]	2016						✓	
Schoenfisch and Stuckenschmidt [85]	2016		✓			✓		
Song et al. [87]	2016	✓				✓		
Bonifati et al. [21]	2017		✓			✓		
Dellal et al. [31]	2017				✓			
Fokou et al. [37]	2017				✓			
Stegemann and Ziegler [89]	2017	✓	✓		✓			
Thakkar et al. [90]	2017	✓						
Akhtar et al. [2]	2018	✓		✓				
Bonifati et al. [22]	2018		✓			✓		
Darari et al. [29]	2018							✓
Martens and Trautner [58]	2018					✓		
Salas and Hogan [76]	2018	✓		✓				
Saleem et al. [78]	2018	✓						
Saleem et al. [80]	2018	✓						
Varga et al. [94]	2018						✓	
Viswanathan et al. [97]	2018				✓			
Akhtar et al. [3]	2019	✓		✓				
Cheng and Hartig [26]	2019	✓	✓			✓		
Fafalios and Tzitzikas [34]	2019							✓
Fernandez et al. [35]	2019	✓						
Potoniec [69]	2019	✓			✓			
Saleem et al. [83]	2019	✓						
Thost and Dolby [91]	2019	✓						✓
Wang et al. [99]	2019				✓			
Savafi et al. [75]	2019			✓				
Singh et al. [86]	2019	✓						✓
Azzam et al. [15]	2020	✓						
Bigerl et al. [18]	2020	✓						
Bonifati et al. [24]	2020		✓		✓	✓		
Figueira et al. [36]	2020		✓			✓		
Jian et al. [47]	2020	✓			✓			
Zhang et al. [102]	2020	✓			✓			
Aebeloe et al. [1]	2021	✓						✓
Almendros-Jimenez et al. [6]	2021	✓			✓			
Azzam et al. [14]	2021	✓						

Table 6
(Continued)

NAME	YEAR	UC 1	UC 2	UC 3	UC 4	UC 5	UC 6	Other
Davoudian et al. [30]	2021	✓						
Desouki et al. [32]	2021	✓						
Röder et al. [74]	2021	✓						
Wang et al. [98]	2021	✓			✓			

found in the property paths, "streaks" that represent a sequence of user reformulations from a seed query, and more besides.

UC3: Caching LSQ can also be used to simulate real workloads for systems that explore caching techniques.

– Knuth et al. [49] propose a middleware component to which applications register and get notifications when the results of their SPARQL queries change; the authors study the problem of scheduling refresh queries for a large number of registered queries and use LSQ to validate their approach.
– Akhtar et al. [2,3] propose an approach to capture changes in an RDF dataset and update a cache system in front of the SPARQL endpoint exposing that data; their approach consists of a change metric that quantifies the changes in an RDF dataset, and a weighting function that assigns importance to recent changes; they use LSQ to verify their approach for real workloads.
– Salas and Hogan [76] propose a method for query canonicalisation, which consists in mapping congruous queries – i.e., queries that are equivalent modulo variable names – to the same query string; their main use case is to increase the hit rate of SPARQL caches, where they use LSQ to test efficiency on real-world queries and to see how many congruent queries can be found in real workloads.
– Savafi et al. [75] study SPARQL adoption using LSQ so they can later provide queries to summarise the Knowledge Graphs such that they can be more efficiently accessed from and stored on mobile devices with limited resources.

UC4: Usability LSQ also has applications for improving the usability of SPARQL endpoints.

– Arenas et al. [11] propose a method for reverse-engineering SPARQL queries, which attempts to construct a query that will return a given set of positive examples as results, but not a second set of negative examples; the authors use LSQ to show that the approach scales well in the data size, number of examples, and in the size of the smallest query that fits the data.
– Benedetti and Bergamaschi [17] present a system (LODeX) that allows users to explore SPARQL endpoints more easily through a formal model defined over the endpoint schema; they show that LODeX is able to generate 77.6% of the 5 million queries contained in the original LSQ dataset.
– Dellal et al. [31] proposes query relaxation methods for queries with empty results, based on finding minimal failing subqueries (generating empty results) and maximal succeeding subqueries (generating non-empty results) to aid the user [37]. The paper refers to LSQ to establish that queries with empty results are common in practice.
– Stegemann and Ziegler [89] propose new operators for the SPARQL language that allow for composing path queries more easily; the authors evaluated their approach with a user study and analysis of the extent to which their language is able to express the real-world queries found in LSQ.
– Viswanathan et al. [97] propose a different form of query relaxation, which generalises a specific resource to a variable on which specific restrictions are added that correspond to relevant characteristics of the resource; they use LSQ to understand how entities are queried in practice.
– Potoniec [69] proposes an interactive system for learning SPARQL queries from positive and negative examples;[15] he uses the DBPEDIA queries of LSQ for experiments.

[15] Notably the system is called Learning SPARQL Queries (LSQ).

- Wang et al. [99] present an approach for explaining missing results for a SPARQL query – based on answering "*why-not*" questions that ask why a specific result is not included – to help users refine their initial queries; the authors search LSQ for queries useful for their approach.
- Bonifati et al. [24] analyse "streaks" in DBpedia query logs,[16] where a streak is defined as a sequence of similar queries in chronological order, capturing the idea of a user refining and/or extending an initial query towards a final query.
- Jian et al. [47] use LSQ to evaluate their approach for SPARQL query relaxation (to generalise users' queries) and query restriction (to refine users' queries) based on approximation and heuristics.
- Zhang et al. [102] propose a method to model client behaviour when formulating SPARQL queries in order to predict their intent and optimise queries. They use LSQ for their evaluation.
- Almendros-Jimenez et al. [6] present two methods for discovering and diagnosing "wrong" SPARQL queries based on ontology reasoning. They evaluate their approach using LSQ queries.
- Wang et al. [98] focus on providing explanations for SPARQL query similarity measures. The authors provide similarity scores using several explainable models based on Linear Regression, Support Vector Regression, Ridge Regression, and Random Forest Regression. They use LSQ to evaluate their query classification.

UC5: Optimisation The LSQ dataset can also be used to identify and study fragments that are commonly used in practice and can be evaluated efficiently using dedicated algorithms.

- The aforementioned analyses by Han et al. [41] and Bonifati et al. [21,22] suggest that well-designed patterns, queries of bounded treewidth, etc., make for promising fragments.
- In the context of probabilistic Ontology-Based Data Access (OBDA), Schoenfisch and Stuckenschmidt [85] analyse the ratio of safe queries – whose evaluation is tractable in data complexity – versus unsafe queries – whose evaluation is #P-hard; they show that over 97.9% of the LSQ queries are safe, and can be efficiently evaluated.
- Song et al. [87] use LSQ to analyse how nested `OPTIONAL` clauses affect query response times; they propose a way to approximate solutions for deeply-nested well-designed patterns.
- Martens and Trautner [58] later take the property paths extracted by Bonifati et al. [21] from LSQ and other sources, defining *simple transitive expressions* that subsume almost all property path expressions seen in practice, while allowing more efficient evaluation than the general case.
- Cheng and Hartig [26] introduce a monotonic version of the `OPTIONAL` operator to SPARQL called `OPT+`; a possible downside of the operator is an increase in query result sizes, where they use the LSQ dataset to study how `OPTIONAL` and `OPT+` behave for real-world queries.
- Building upon the work of Martens and Trautner [58], Figueira et al. [36] specifically study the containment problem for restricted classes of Conjunctive Regular Path Queries (CRPQs), which are akin to BGPs with property paths; aside from complexity results, they show the coverage of the different classes for logs that include LSQ [24].

UC6: Meta-querying A handful of works have also used LSQ in the context of meta-querying, where queries are found based on the resources they contain.

- Rico et al. [71] observe that analogous DBpedia properties are often defined in two distinct namespaces – e.g., `dbo:birthPlace` and `dbp:birthPlace` – where they propose methods to automatically expand SPARQL queries to capture solutions involving analogous properties; they show that only 0.2% of the DBpedia queries in LSQ mention properties from both namespaces.
- Varga et al. [94] provide an RDF-based metamodel for BI 2.0 systems, which allows for capturing the schema of a dataset, as well as previous queries that have been posed against that dataset by other users; the authors propose to re-use parts of the LSQ vocabulary in their model; they further instantiate their model using LSQ to retrieve queries asked about countries.

[16] In fact, these logs were gathered directly from OpenLink, though we include discussion since similar analysis could have been applied to the LSQ logs, and LSQ logs where used in other analyses.

Other use cases A number of works have used LSQ (mostly for evaluation) in contexts that were not originally anticipated by the aforementioned use cases.

– Georgala et al. [39] propose a method to predict temporal relations between events represented by RDF resources following Allen's interval algebra; they use LSQ to validate their approach considering query executions as events.
– Darari et al. [29] present a theoretical framework for augmenting RDF data sources with completeness statements, which allows for reasoning about the completeness of SPARQL query results; they evaluate their method using LSQ.
– Fafalios and Tzitzikas [34] present a query evaluation strategy, called SPARQL-LD, that combines link traversal and query processing at SPARQL endpoints; they provide a method for checking if a SPARQL query can be answered through link traversal, and analyse a large corpus of real SPARQL query logs – including LSQ – for finding the frequency and distribution of answerable and non-answerable query patterns; they also use LSQ to evaluate their approach.
– Singh et al. [86] use the LSQ vocabulary for providing a benchmark for Question Answering over Linked Data. The authors use the LSQ vocabulary to represent the SPARQL query related features prior to generating the benchmark.
– Thost and Dolby [91] present QED: a system for generating concise RDF graphs that are sufficient to produce solutions from a given query, which can be used for benchmarking, for compliance testing, for training query-by-example models, etc.; they apply their system over LSQ queries to generate datasets from DBPEDIA.
– Aebeloe et al. [1] present a decentralised architecture based on blockchain that allows users to propose updates to faulty or outdated data, tracing back their origin, and query older versions of the data. They use LSQ queries for their evaluation.

Discussion Per Table 6, we see that the original version of LSQ has been used in a wide variety of research works for a variety of purposes. Complementing other SPARQL query logs such as Wikidata's [57], we believe that LSQ 2.0, with its extended set of queries, will likewise serve as a useful resource to help align the theory and practice of SPARQL research.

8. Conclusions and future directions

In this paper, we have described the Linked SPARQL Queries v.2 (LSQ 2.0) dataset, which represents queries in logs as RDF, allowing clients to quickly find real-world queries that may be of interest to them. We have described a number of use cases for LSQ, including the generation of custom benchmarks, the analysis of how SPARQL is used in practice, the evaluation of caching systems, the exploration of techniques to improve the usability of SPARQL services, the targeted optimisation of queries with characteristics commonly found in real workloads, as well as the ability to find queries relating to specific resources. We then described the model and vocabulary used to represent LSQ, including static features of queries, a SPIN representation, provenance encoding the agents and endpoints from which the query originate, as well as runtime statistics generated through local executions of the queries against their corresponding dataset. We then discussed how LSQ is published, thereafter describing the datasets and queries featured in the current version of LSQ. Finally we discussed how LSQ has been used for research purposes since its initial release in 2015.

As discussed in Section 7, since its initial release, LSQ has been adopted by a variety of research works for a variety of purposes. In terms of future directions, we will look to continue adding further logs with further queries to the dataset. Looking at how LSQ has been adopted in the literature has also revealed ways in which the metadata for LSQ could be extended in a future version, such as to add information about monotonicity and satisfiability [41], or information about (hyper)treewidth [21,22], for example. It may also be useful to provide a canonical version of the query string [76]; this could perhaps be leveraged, for example, when evaluating caching methods. Another useful feature would be to add questions in natural language that verbalise each query, which could be used, for example, in order to create datasets for training and testing question answering systems, as well as enabling users to find relevant queries through keyword search; given the large number of queries in the dataset, an automated approach may be applicable [64].

As discussed by Martens and Trautner [59], query logs allow to bridge the theory and practice of SPARQL. They serve an important role, ensuring that the research conducted by the community is guided by the requirements and trends that emerge in practice. We thus believe that LSQ (2.0) will continue to serve an important role in SPARQL research in the coming years.

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