

How do Semantic Web, Linked Data, Open Data, and Knowledge Graphs interplay?



Axel Polleres

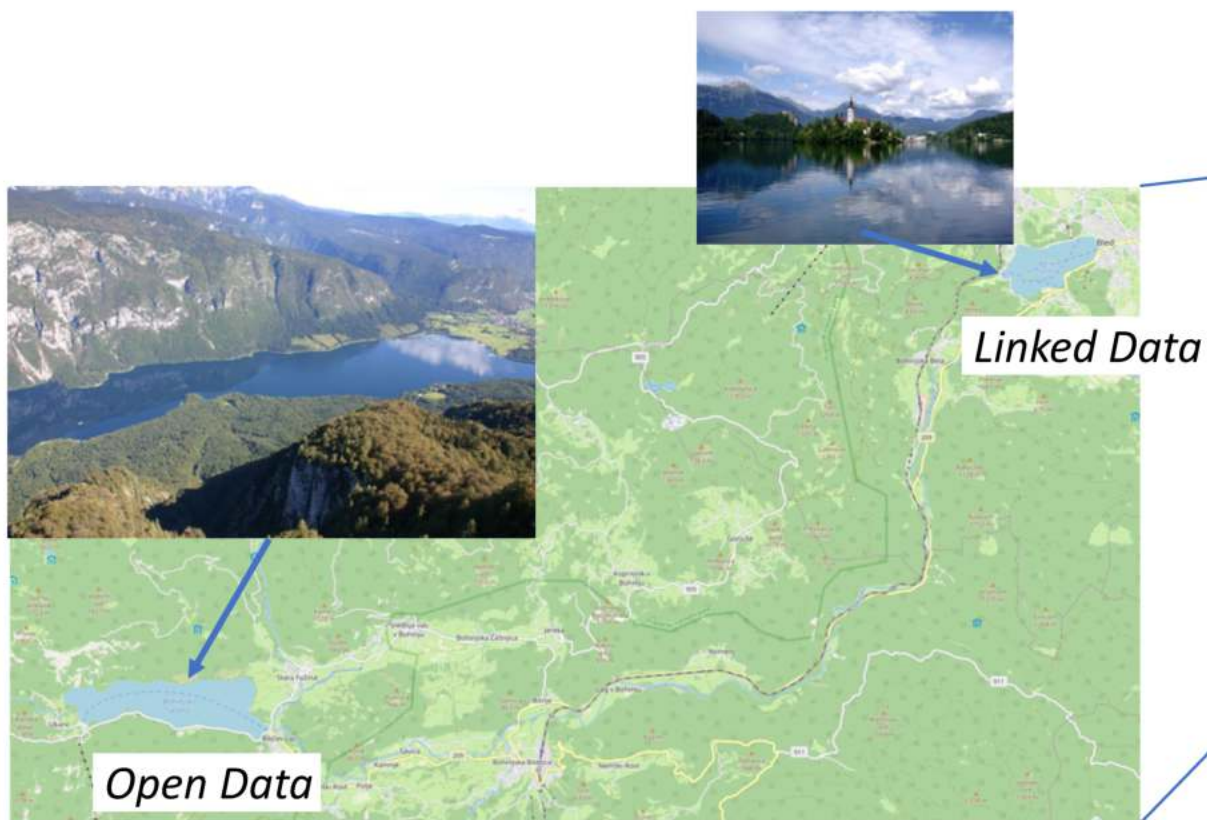
Semantic Web, Linked Data, Open Data, Knowledge Graphs ... travel report from a personal journey



Disclaimer: just like any trip report, this talk might be opinionated and influenced by personal experiences

Trip map... (incl. some “data lakes”)

- From Semantic Web to Linked Data
- From Linked Data to Open Data
- From Linked Data to Knowledge Graphs
- From Knowledge Graphs to Semantic Web



From Semantic Web to Linked Data

- (early 2000s)



The Semantic Web

A new form of Web content that is meaningful to computers will unleash a revolution of new possibilities

by [TIM BERNERS-LEE](#), [JAMES HENDLER](#) and [ORA LASSILA](#)

The entertainment system was belting out the Beatles' "We Can Work It Out" when the phone rang. When Pete answered, his phone turned the sound down by sending a message to all the other *local* devices that had a *volume control*. His sister, Lucy, was on the line from the doctor's office: "Mom needs to see a specialist and then has to have a series of physical therapy sessions. Biweekly or something. I'm going to have my agent set up the appointments." Pete immediately agreed to share the chauffeuring. At the doctor's office, Lucy instructed her Semantic Web agent through her handheld Web browser. The agent promptly retrieved information about Mom's *prescribed treatment* from the doctor's agent, looked up several lists of *providers*, and checked for the ones *in-plan* for Mom's insurance within a *20-mile radius* of her *home* and with a *rating of excellent* or *very good* on trusted rating services. It then began trying to find a match between available *appointment times* (supplied by the agents of individual providers through their Web sites) and Pete's and Lucy's busy schedules. (The emphasized keywords indicate terms whose semantics, or meaning, were defined for the agent through the Semantic Web.)

In a few minutes the agent presented them with a plan. Pete didn't like it—University Hospital was all the way across town from Mom's place, and he'd be driving back in the middle of rush hour. He set his own agent to redo the search with stricter preferences about *location* and *time*. Lucy's agent, having *complete trust* in Pete's agent in the context of the present task, automatically assisted by supplying access certificates and shortcuts to the data it had already sorted through.

<https://1n.pm/A5psO>

Expressing Meaning
Knowledge Representation
Ontologies
Agents
Evolution of Knowledge

From Semantic Web to Linked Data

- (early 2000s)

Evolution of Knowledge
Agents

Ontologies (OWL)

Knowledge Representation (RDFS)

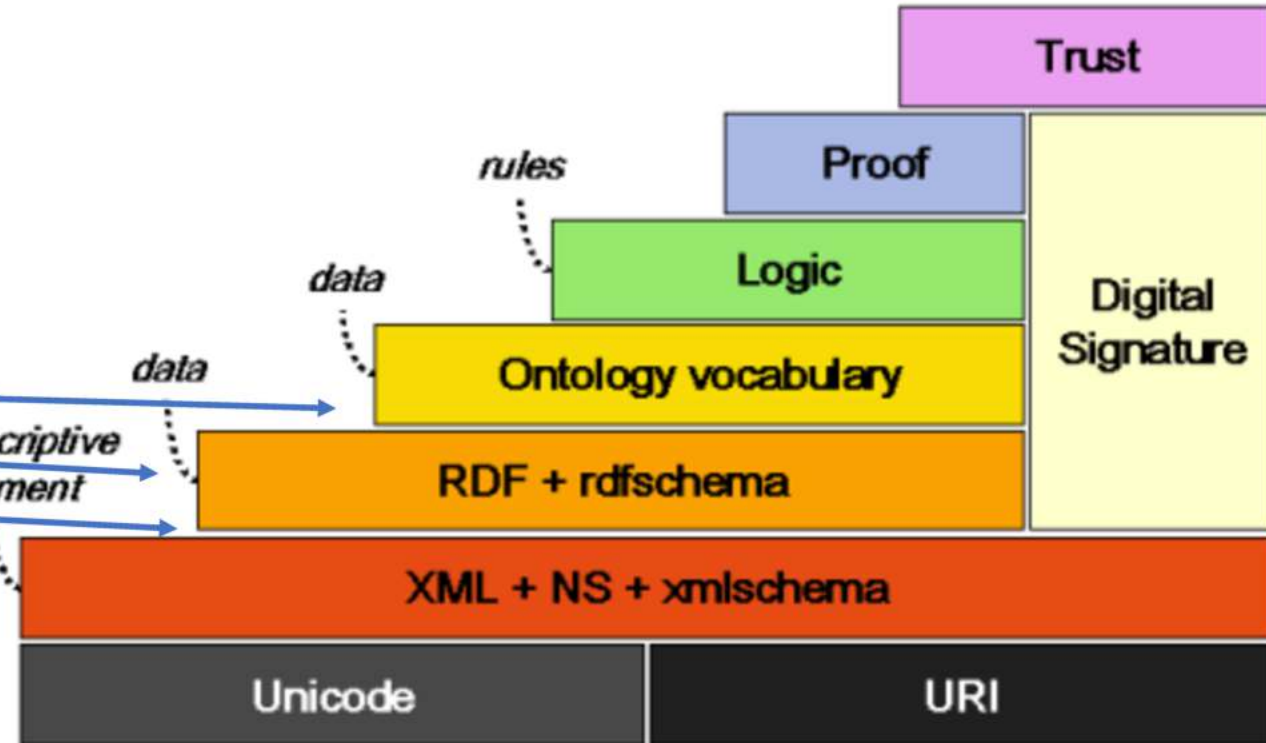
Expressing Meaning (URLs and RDF)

*selfdescriptive
document*

data

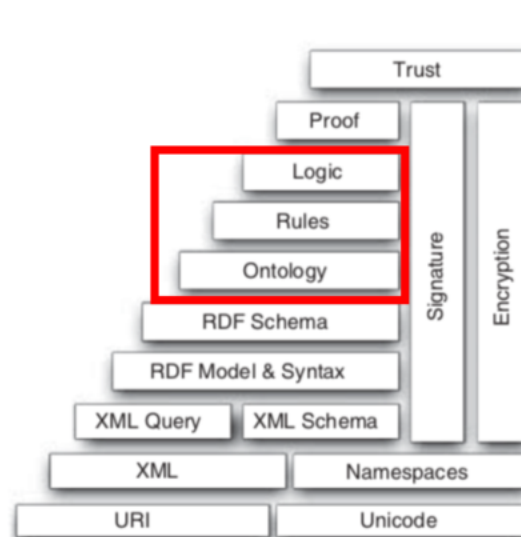
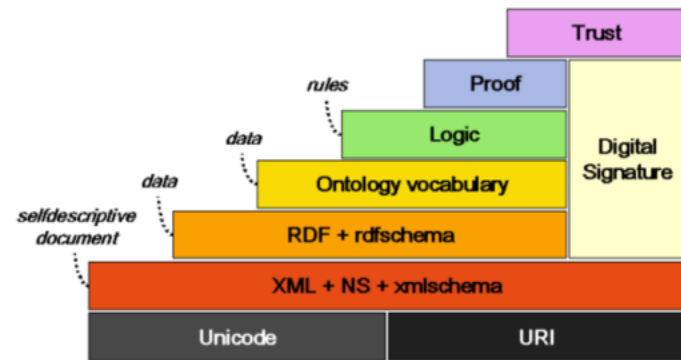
data

rules



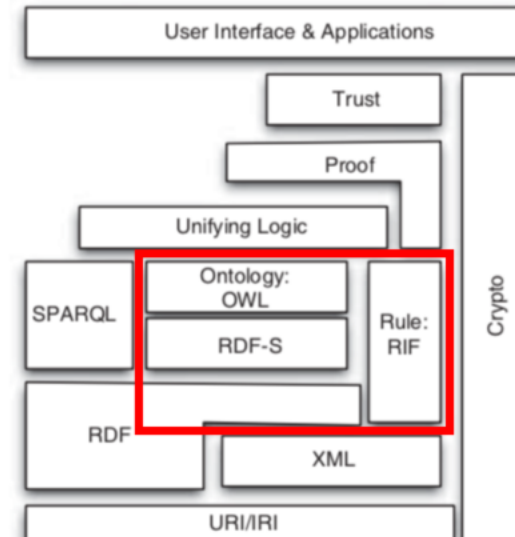
From Semantic Web to Linked Data

- (2000s - ca. 2009)



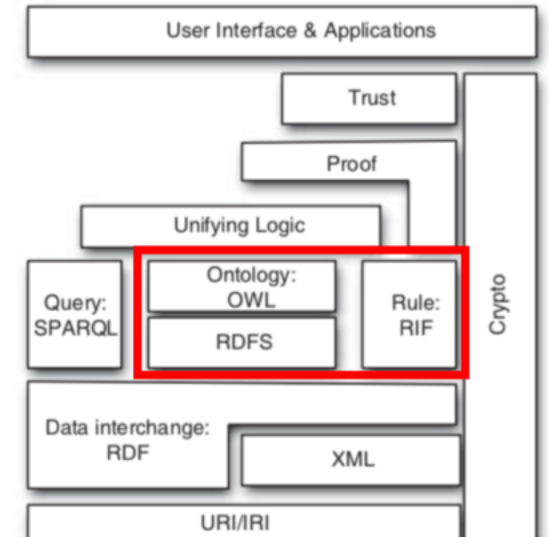
2004^a

^ahttp://www.w3.org/2004/Talks/0319-RDF-WGs/sw_stack.png



2007^b

^b<http://www.w3.org/2007/Talks/0130-sb-W3CTechSemWeb/layerCake-4.png>



2009^c

^c<http://www.w3c.it/talks/2009/athena/images/layerCake.png>

From Semantic Web to Linked Data

- (2000s - ca. 2009)

- Main (distracting?) question: what is the “right” knowledge representation and logic to express “Knowledge on the Web”?

- Description Logics?

- Rules? (Datalog, Deductive Databases)

- Nonmonotonic Logic Programming/Default Reasoning

- Open World Assumption vs. Closed World Assumption?

- “Local Closed-World assumption”/“Contextually scoped negation”

- Unique Names Assumption vs. Non-unique names

My Web site is about *thrillers*,
Psycho is a thriller
all *thrillers* are *movies*

All horror movies
except comedies
are *thrillers*

*Is Nightmare
on Elm Street
a comedy?*



www.imdb.com/title/tt0175142/
vs.
en.wikipedia.org/wiki/Scary_Movie

All horror movies *listed on my Website* except
comedies listed on IMDB are thrillers



From Semantic Web to Linked Data

My Web site is about *Thrillers*, all *thrillers* are *movies*

- (2000s - ca. 2009)

Semantic Web Architecture: Stack or Two Towers?

Ian Horrocks¹, Bijan Parsia², Peter Patel-Schneider³, and James Hendler²

¹ School of Computer Science
University of Manchester, UK

www.cs.man.ac.uk/~horrocks/

² Maryland Information and Network Dynamics Laboratory
University of Maryland

Keep DL and Rules separate?

Work on Unified Logics?

bases)
programming/Default Reasoning vs. Closed World Assumption
in vs. Non-unique names
"assumption"/"Contextually scoped

Abstract. We discuss language architecture for the Semantic Web, and in particular different proposals for extending this architecture with a rules component. We argue that an architecture that maximises compatibility with existing languages, in particular RDF and OWL, will benefit the development of the Semantic Web, and still allow for forms of closed world assumption and negation

**Good news! Boost in KR research:
We know very well which ontological reasoning approaches are decidable and how they scale**

→ OWL2, OBDA

DL+log: Tight Integration of Description Logics and Disjunctive Datalog

Riccardo Rosati
Dipartimento di Informatica e Sistemistica
Università di Roma "La Sapienza"
Via Salaria 113, 00198 Roma, Italy
rosati@ma1.it

Rules with Contextually Scoped Negation

Axel Polleres^{1,2}, Cristina Feier¹, and Andreas Harth¹
¹ Digital Enterprise Research Institute Innsbruck, Austria and Galway, Ireland
² Universidad Rey Juan Carlos, Madrid, Spain
axel@polleres.net, {cristina.feier, andreas.harth}@deri.org

Contextualized Reasoning?

Abstract. This paper discusses representation formalisms used on the Semantic Web, in particular the closed world assumption. Therefore, nonmonotonic logic is necessary to deal with scepticism. Especially negation in OWL is notoriously problematic. In ongoing discussions about extending OWL to allow for scoped negation, the semantics of such "scoped" negation is missing. We propose a semantics for such "scoped" negation and discuss two possible semantics. We argue that this class of logic programs can be viewed as a rule extension to a subset of RDF(S).

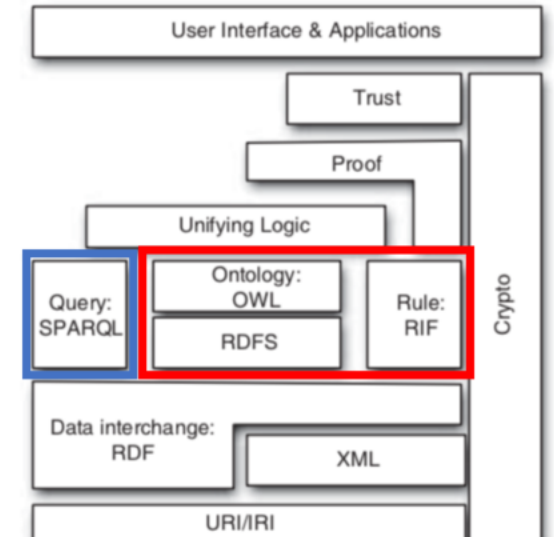
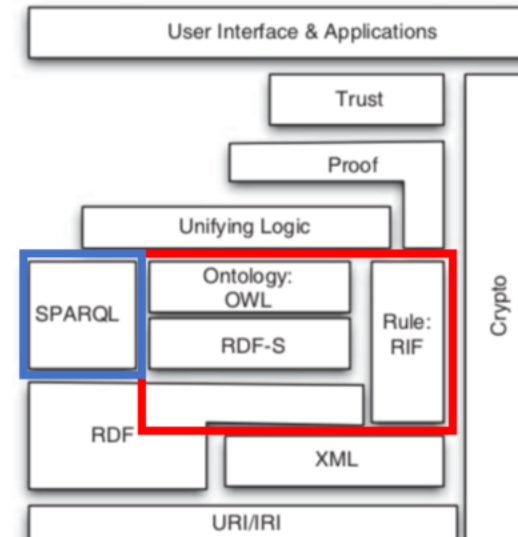
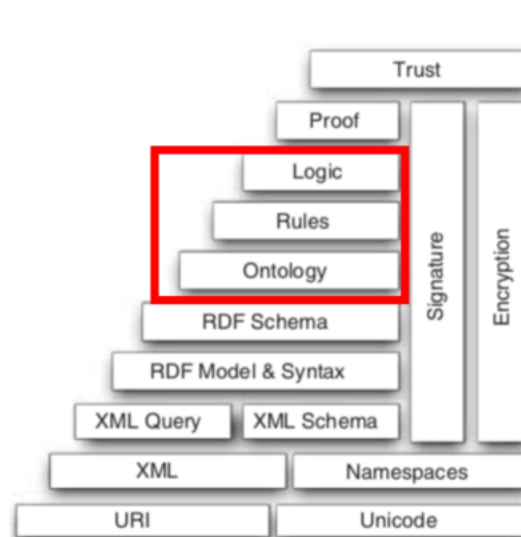
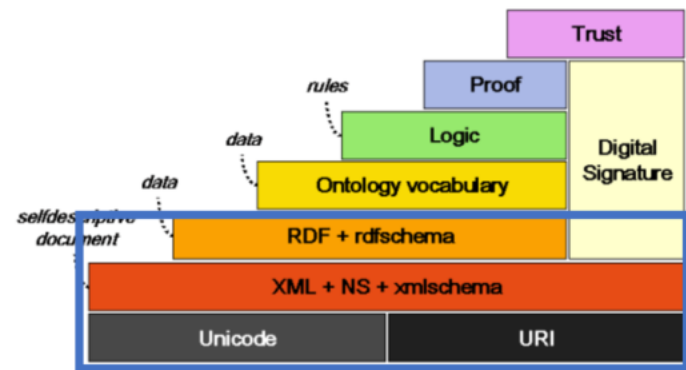
horror movies
apt comedies
e thrillers



wikipedia.org/wiki/Scary_Movie

From Semantic Web to Linked Data

- (2000s - ca. 2009)



2004^a

^a<http://www.w3.org/2004>

^b<http://www.w3.org/2007>

^c<http://www.w3c.it/talks>

2007^b

2009^c

What about the **data**???

How much ontological Reasoning and Expressivity does the **Web** actually need?

From Semantic Web to Linked Data

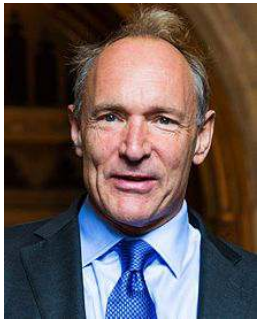
- (ca. 2006/7 – ca. 2013)
 - Main question: How can I **publish** “Knowledge on the Web” in order to enable **answering structured queries**?



What about the **data**???

From Semantic Web to Linked Data

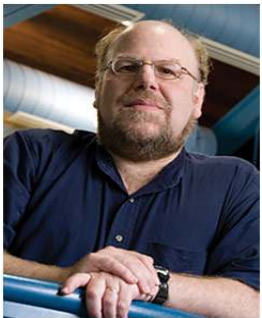
- (ca. 2006/7 – ca. 2013)
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Linked Data Principles

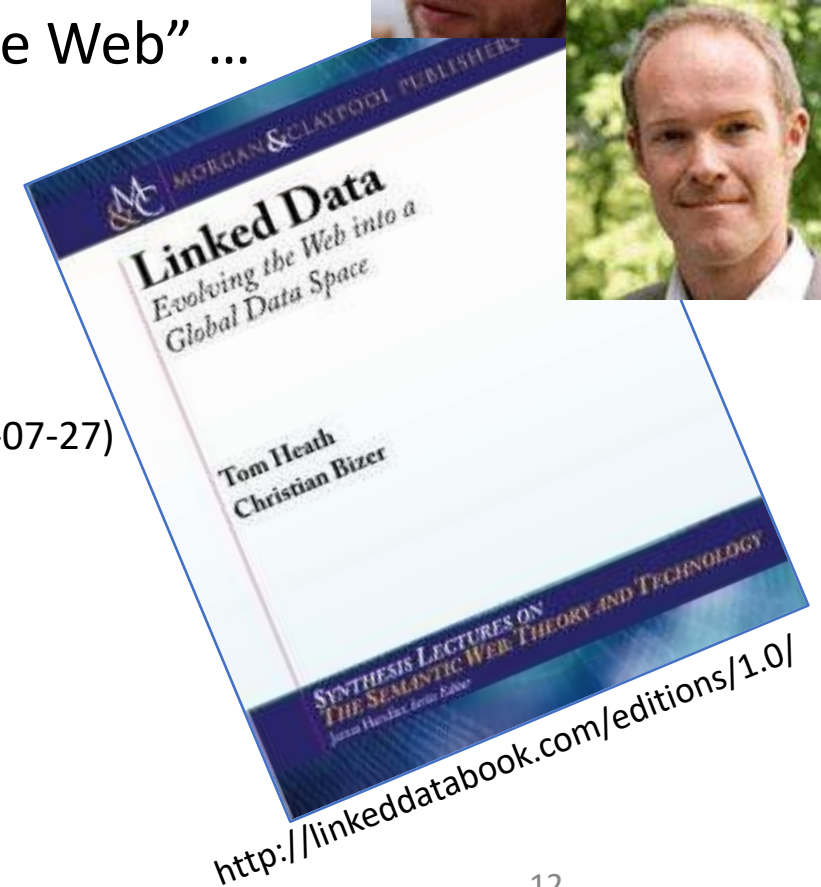
- **LDP1:** use URIs as names for things
- **LDP2:** use HTTP URIs so those names can be dereferenced
- **LDP3:** return useful – RDF? – information upon dereferencing those URIs
- **LDP4:** include links using externally dereferenceable URIs.

<https://www.w3.org/DesignIssues/LinkedData.html> (originally published 2006-07-27)



“A Little Semantics Goes a Long Way” (Jim Hendler)

<https://www.cs.rpi.edu/~hendler/LittleSemanticsWeb.html>



From Semantic Web to Linked (Open) Data

- (ca. 2006/7 – now)
 - Main question: How can I **publish** “Knowledge on the Web” ...

Linked Data Principles

- **LDP1:** use URIs as names for things
- **LDP2:** use HTTP URIs so those names can be dereferenced
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- **LDP4:** include links using externally dereferenceable URIs.

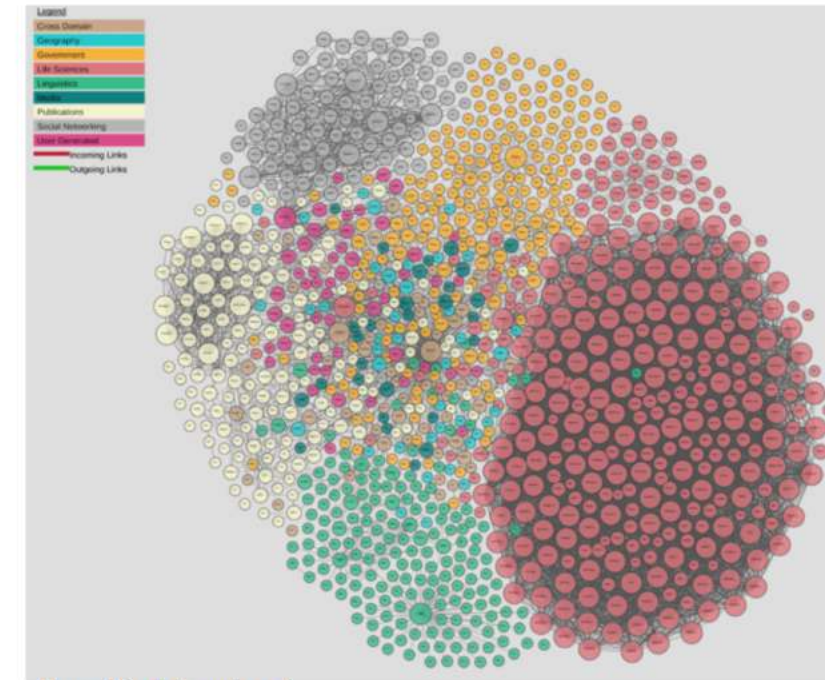
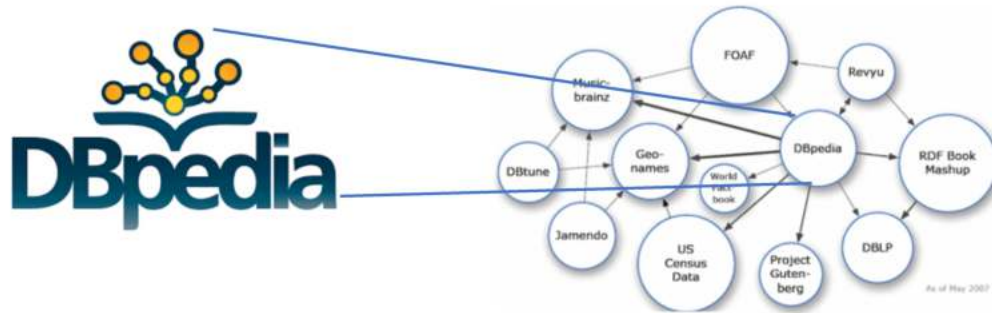


+ <https://www.w3.org/community/webize/2014/01/17/what-is-5-star-linked-data/>

★	Available on the web (whatever format) <i>but with an open licence, to be Open Data</i>
★★	Available as machine-readable structured data (e.g. excel instead of image scan of a table)
★★★	as (2) plus non-proprietary format (e.g. CSV instead of excel)
★★★★	All the above plus, Use open standards from W3C (RDF and SPARQL) to identify things, so that people can point at your stuff
★★★★★	All the above, plus: Link your data to other people's data to provide context

From Semantic Web to Linked (Open) Data

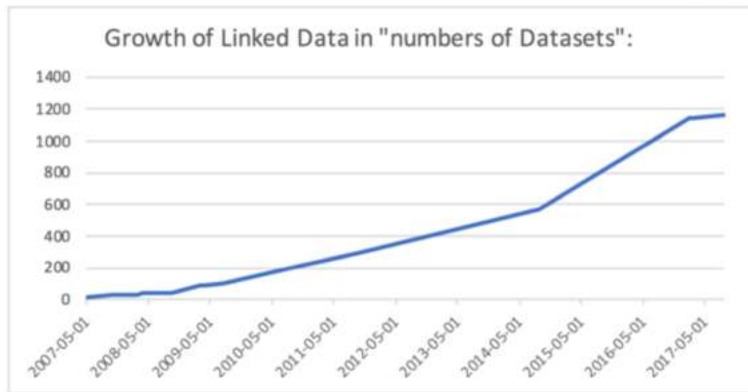
- (ca. 2006/7 – now)
 - Main question: How can I **publish** “Knowledge on the Web” ...
 - Linked Open Data... growth since ~10 years
 - A lot of active developments to publish and link RDF Data



<http://lod-cloud.net/>

2017-08-22
2017-02-20
2017-01-26
2014-08-30
2011-09-19
2010-09-22
2009-07-14
2009-03-27
2009-03-05
2008-09-18
2008-03-31
2008-02-28
2007-11-10
2007-11-07
2007-10-08
2007-05-01

1163
1139
1146
570
295
203
95
93
89
45
34
32
28
28
25
12



Axel Polleres, Maulik R. Kamdar, Javier D. Fernández, Tania Tudorache, and Mark A. Musen. [A more decentralized vision for linked data](#). In *Decentralizing the Semantic Web (Workshop of ISWC2018)*.

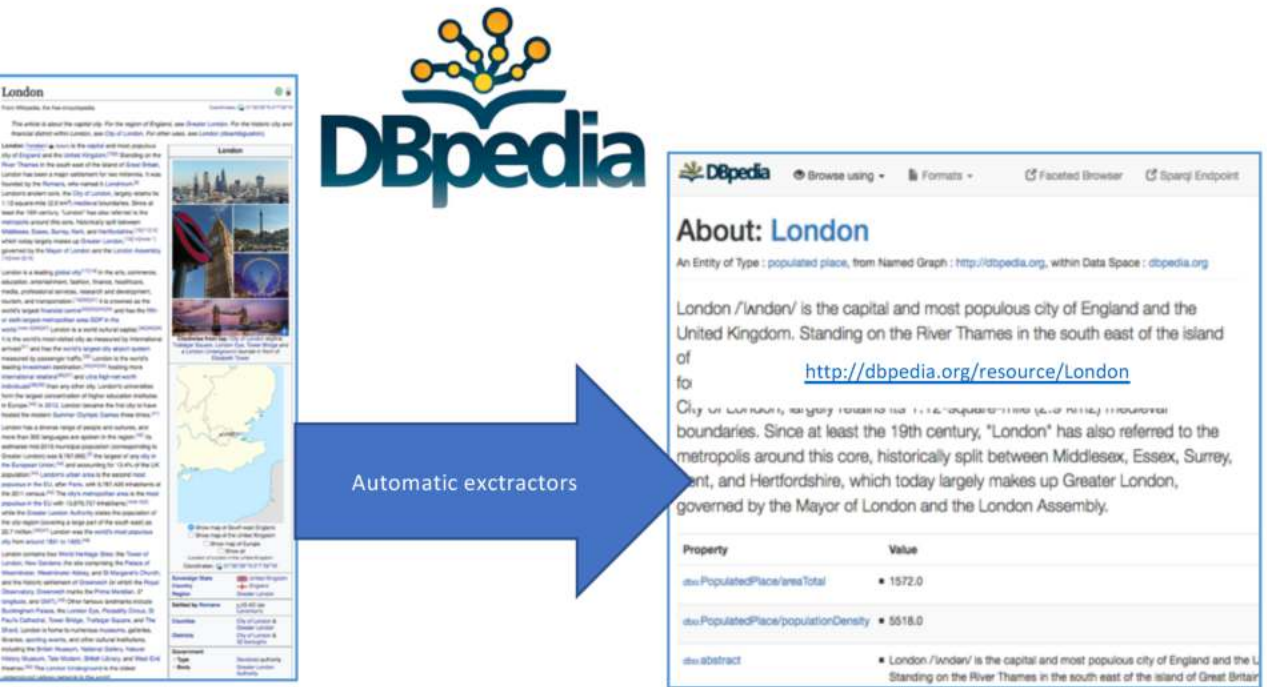
From Semantic Web to Linked (Open) Data

- (ca. 2006/7 – now)

- Main question: How can I **publish** “Knowledge on the Web” ...

in order to enable **answering structured queries?**

→ **SPARQL**



Which cities in the UK have more than 1M people?

```
http://yasgui.org/short/UVOyhX8ft

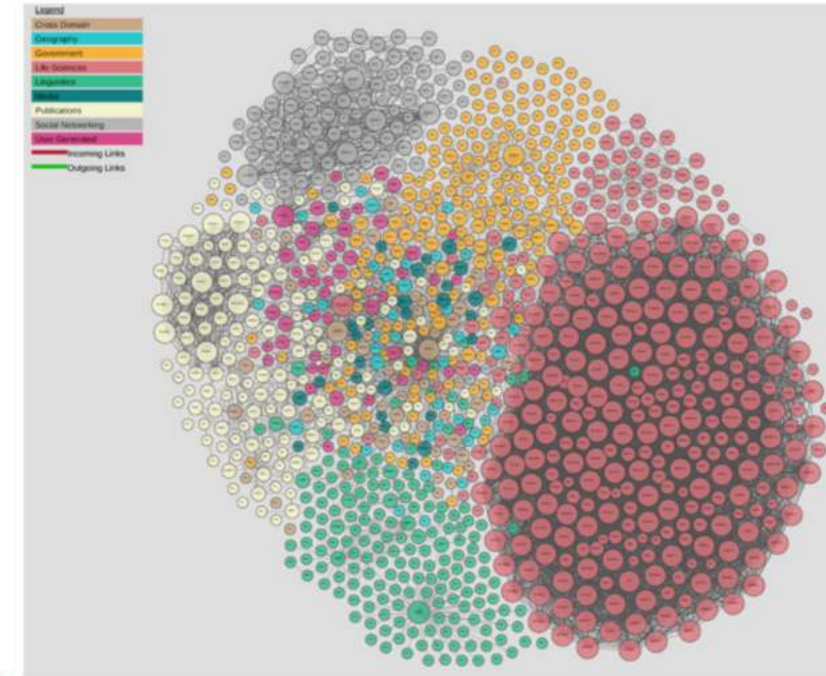
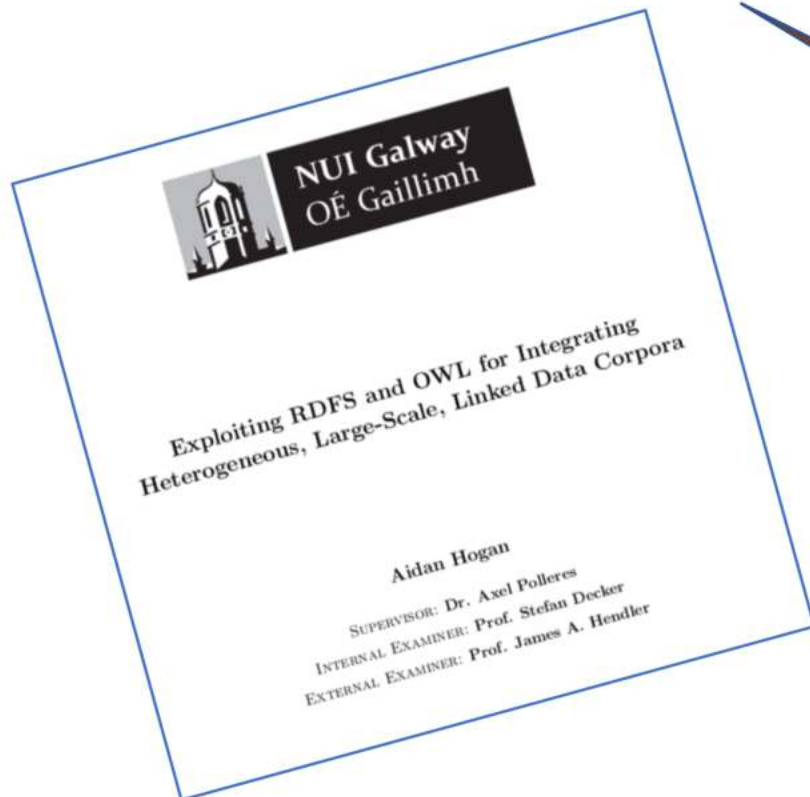
PREFIX : <http://dbpedia.org/resource/>
PREFIX dbo: <http://dbpedia.org/ontology/>
PREFIX yago:
<http://dbpedia.org/class/yago/>

SELECT DISTINCT ?city ?pop WHERE {
  ?city a yago:City108524735 .
  ?city dbo:country :United_Kingdom.
  ?city dbo:populationTotal ?pop

  FILTER ( ?pop > 1000000 )
}
```

From Semantic Web to Linked (Open) Data

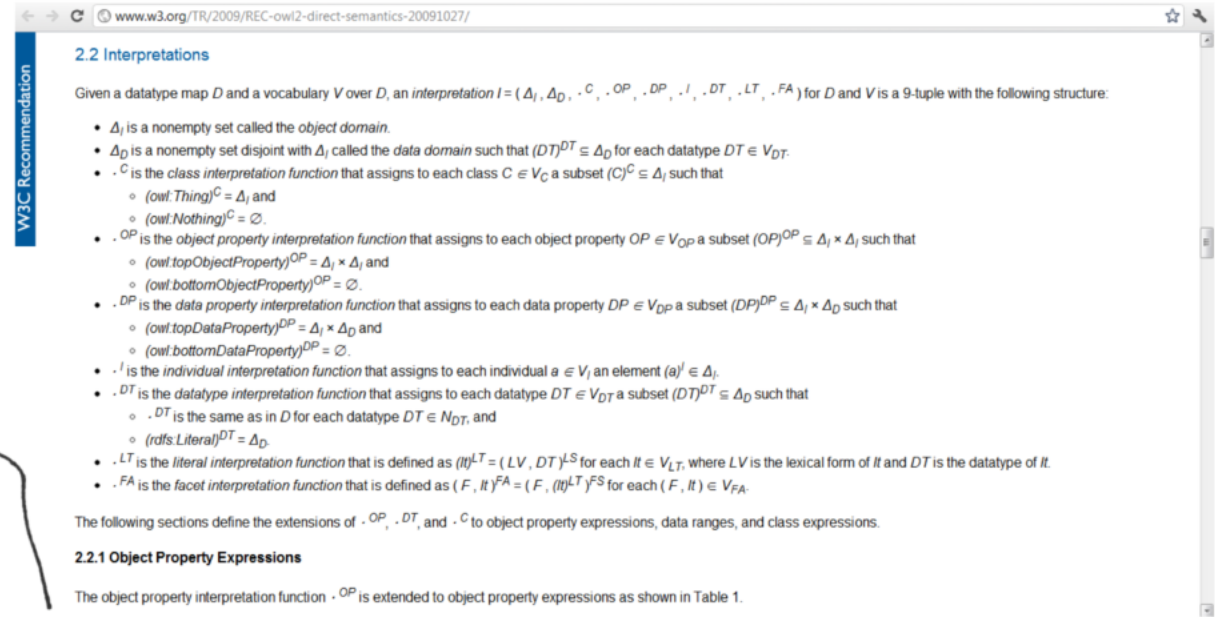
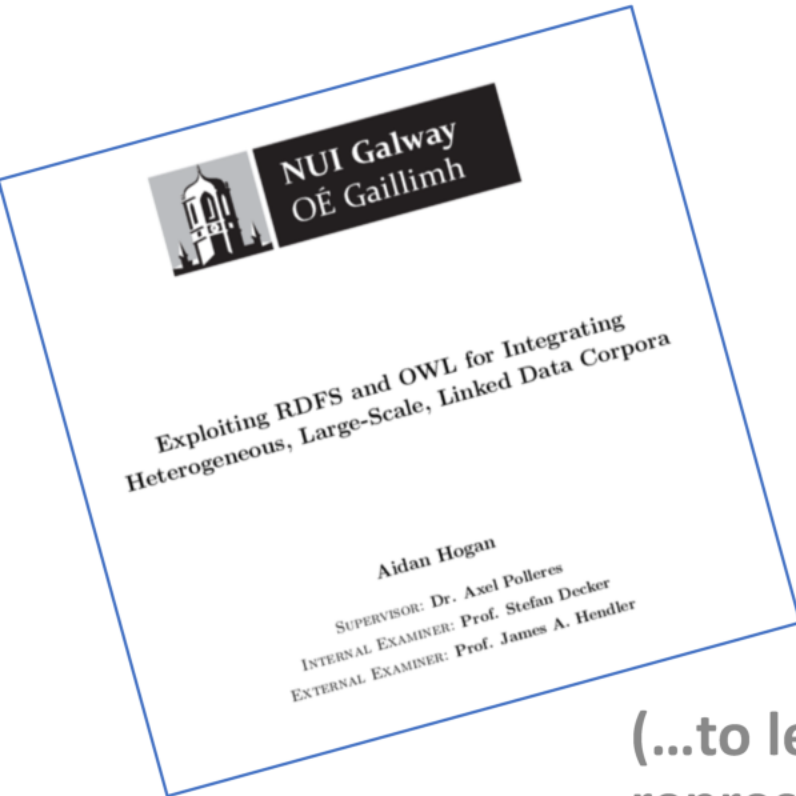
- (ca. 2006/7 – now)
 - Linked Open Data... growth since ~10 years
 - A lot of active developments to publish and link RDF Data



How much ontological Reasoning and Expressivity does the **Web** actually need?



Main insight: OWL is (too?) hard



(...to learn, to understand, to implement, to compute, to teach, to represent in RDF, to publish, to parse, to use *appropriately*...)

...for Linked Data publishers

Linked Data publishers only use a little bit of OWL ...

... they still manage to make mistakes 😊

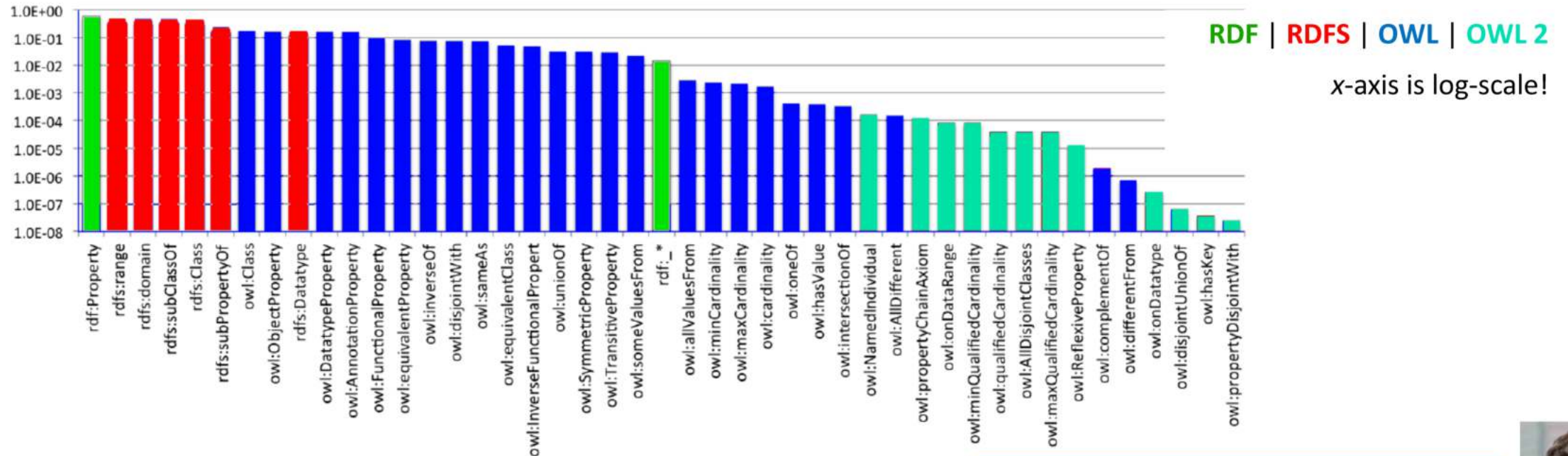
Cautious OWL inference can still help to enrich Linked Data!

How much ontological Reasoning and Expressivity does the Web actually need?



Linked Data publishers only use a little bit of OWL ...

- RDFS features amongst the most prominently used
- OWL 2 features hardly used
- The commonly used features are a fragment of OWL RL (*i.e., fragment of OWL where Description Logics and Datalog Rules coincide*)



How much ontological Reasoning and Expressivity does the **Web** actually need?



Linked Data publishers still manage to make mistakes 😊



DBpedia Browse using - Formats - Faceted Browser Sparql Endpoint

About: European Union

An Entity of Type : populated place, from Named Graph : http://dbpedia.org, within Data Space : dbpedia.org

The European Union (EU) is a politico-economic union of 28 member states that are located primarily in Europe. It has an area of 4,324,782 km2 (1,669,808 sq mi) and an estimated population of over 510 million. The EU has developed a

- rdf:type
- owl:Thing
 - dbo:Place
 - dbo:Location
 - wikidata:Q6256
 - **dbo:Country**
 - **dbo:Organisation**
 - dbo:PopulatedPlace
 - geo:SpatialThing

DBpedia Ontology:

dbo:Agent *owl:disjointWith* dbo:Place.

dbo:Country rdfs:subClassOf dbo:Place.

dbo:Organisation rdfs:subClassOf dbo:Agent.



Other issue: **Ontology "Hijacking"**

i.e., publishers re-defining others' ontologies by adding inconsistent axioms

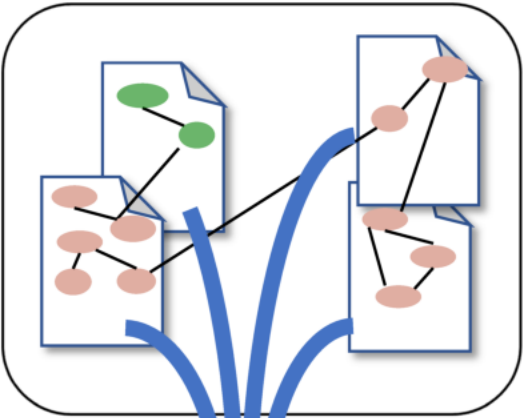
How much ontological Reasoning and Expressivity does the **Web** actually need?



Cautious OWL inference can still help to enrich Linked Data and can be implemented in a scalable manner!

... based on these insights we have implemented a Semantic Web Search Engine (SWSE)

robust & scalable inference for Linked data:

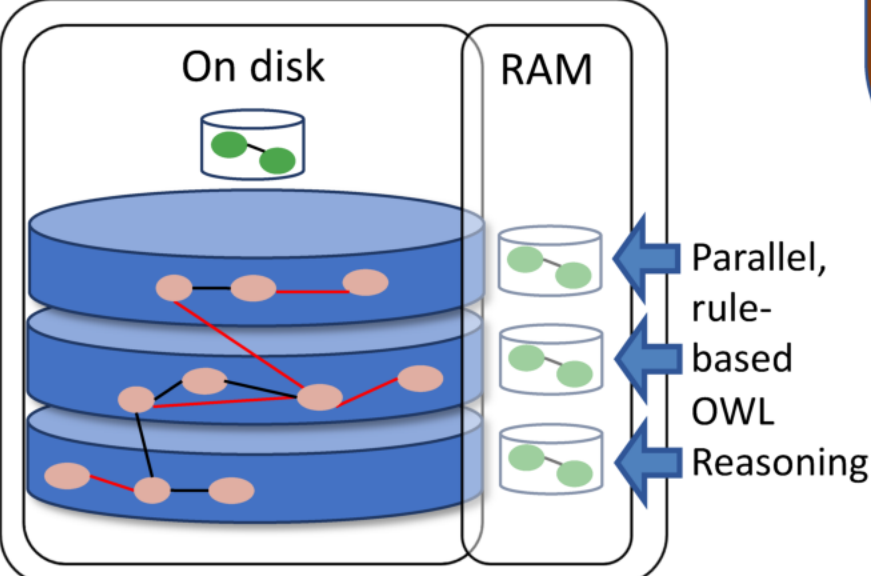


Good News!

Cautious OWL inference = **deductive, rule-based inference**, plus some **heuristics** on provenance and confidence to avoid non-sensual inferences and resolve inconsistencies

enables Semantic Search and Querying over (5-star) Linked Open Data!

Crawling
Indexing



How much ontological Reasoning and Expressivity does the **Web** actually need?



From Linked Data to Open Data

- (ca. 2009 - now) Open Data has become a global trend!

EU & Austria, but also the (previous) US and UK administrations are/were pushing Open Data!



Open Data Österreich

Suchbegriff

24.818 Datensätze 465 Anwendungen 60 Organisationen

Arbeitsplätze Bevölkerung Bildung & Forschung Finanzen & Rechnungswesen Geographie & Planung Gesundheit & Soziales Gesundheit

DATA.GOV DATA TOPICS IMPACT APPLICATIONS DEVELOPERS CONTACT

The home of the U.S. Government's open data

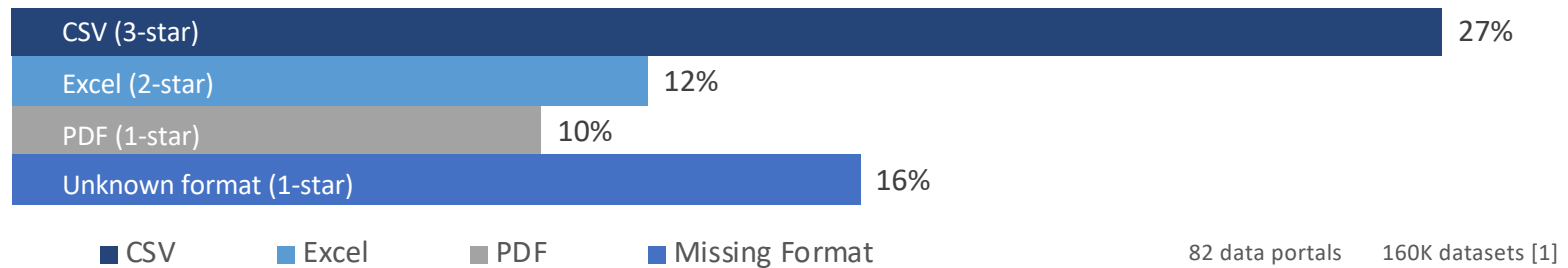
Here you will find data, tools, and resources to conduct research, develop web and mobile applications, design data visualizations, and [more](#).

GET STARTED
SEARCH OVER 170,714 DATASETS

Federal Student Loan Program Data

From Linked Data to Open Data

- However...
- Available data is only partially structured and not linked [1]:



Non-Linked Open Data is growing still much faster than Linked Open Data on the Web

[1] Umbrich, J., Neumaier, S., Polleres, A.: Quality assessment & evolution of open data portals. International Conference on Open and Big Data (2015)

Open Data as a Global Trend:

Country	URL	Datasets
United States	data.gov	170.7k
Canada	open.canada.ca	79.1k
UK	data.gov.uk	45.1k
France	www.data.gouv.fr	34.2k
Russia	opengovdata.ru	30.3k
Japan	data.go.jp	21k
Italy	dati.gov.it	20.4k
Germany	govdata.de	19.8k

Actually, over 235k!

Data portals of the G8 countries

Open Data portals...

Uniform metadata, accessible via common APIs (JSON), mostly not yet RDF.

DATA.GOV DATA TOPICS - IMPACT APPLICATIONS DEVELOPERS CONTACT

DATA CATALOG / Datasets Organizations

Department of Housing and Urban Development / US Department of Housing and Urban Development

Housing Affordability Data System (HADS)

Metadata Updated: March 8, 2017

The Housing Affordability Data System (HADS) is a set of files derived from the 1985 and later national American Housing Survey (AHS) and the 2002 and later Metro AHS. This system categorizes housing units by affordability and households by income, with respect to the Adjusted Median Income, Fair Market Rent (FMR), and poverty income. It also includes housing cost burden for owner and renter households. These files have been the basis for the worst case needs tables since 2001. The data files are available for public use, since they were derived from AHS public use files and the published income limits and FMRs. These datasets give the community of housing analysts the opportunity to use a consistent set of affordability measures.

Access & Use Information

- Public:** This dataset is intended for public access and use.
- License:** No license information was provided. If this work was prepared by an officer or employee of the United States government as part of that person's official duties it is considered a U.S. Government Work.

Downloads & Resources

- Comma Separated Values File (17730 views) Download

Dates

Metadata Created Date	March 7, 2014
Metadata Updated Date	March 8, 2017

Metadata Source

Data.gov Metadata

Harvested from HUD JSON

affordability cost fmr households housing income rent renter

Additional Metadata

Resource Type	Dataset
Metadata Created Date	March 7, 2014
Metadata Updated Date	March 8, 2017
Publisher	US Department of Housing and Urban Development
Unique Identifier	HUD033
Maintainer	Shula Markland
Maintainer Email	Shula.Markland@HUD.gov

data.gv.at Suchbegriff (z.B. Finanzen, Wahlen) Suche starten

Datenkatalog Apps & News Katalog durchstöbern

data.gv.at - offene Daten Österreichs

Startseite Daten Dokumente Anwendungen

Katalog Bildungsausgaben

Bildungsausgaben;Regionale Gliederung;Bildungseinrichtung

Veröffentlichende Organisation bzw. Person: Statistik Austria

Kategorie: Bildung und Forschung; Finanzen und Rechnungswesen; Wirtschaft und Tourismus

Daten und Ressourcen

- OGD_bildungsausgaben_BILDAUS_1 Entdecke
- OGD_bildungsausgaben_BILDAUS_1_HEADER Entdecke
- OGD_bildungsausgaben_BILDAUS_1_C-A10-0 Entdecke
- OGD_bildungsausgaben_BILDAUS_1_C-BARG-0 Entdecke
- OGD_bildungsausgaben_BILDAUS_1_C-BABE1-0 Entdecke

Titel und Beschreibung Englisch: Educational expenditure

Veröffentlichende Stelle: Statistik Austria

Datenverantwortliche Stelle: Statistik Austria, Guglgasse 13, 1110 Wien, Austria

Kontaktseite der datenverantwortlichen Stelle: http://www.statistik.at/web_de/kontakt

Datenverantwortliche Stelle - E-Mailkontakt: open.data@statistik.gv.at

Lizenz: Creative Commons Attribution License

Lizenz Zitat: Datenquelle: CC-BY-3.0: Statistik Austria - data.statistik.gv.at

Link zur Lizenz: <https://creativecommons.org/licenses/by/3.0/>

Weiterführende Metadaten - Link: <http://statcube.at/statcube/opedatabase?id=debildungsausgaben>; http://www.statistik.at/web_de/statistiken/bildung_und_kultur/formales_bildungswesen/bildungsausgaben/index.html; http://www.statistik.at/web_en/statistics/education_culture/formal_education/educational_expenditure/index.html

API - Link zu allen Metadaten: /api/3/action/package_show?id=71137735-2c65-328f-b57d-be941ada765e

RSS-Feeds für Statistik Austria: [geänderte Datensätze](#)

Letzte Änderung: 30.04.2018 00:59:46

eurostat Your key to European statistics

Legal notice | RSS | Cookies | Links

News Data Publications About Eurostat Help

European Commission > Eurostat > Cities (Urban Audit) > Data > Database

CITIES (URBAN AUDIT) **DATABASE**

Overview 'Regions & cities'

Background

Data

- City statistics (urb)
- Cities and greater cities (urb_cgct)
- Population on 1 January by age groups and sex - cities and greater cities (urb_cpop)
- Population structure - cities and greater cities (urb_cpopstr)
- Population by citizenship and country of birth - cities and greater cities (urb_cpopcit)
- Fert
- Liv
- Edu
- Cult
- Lab
- Eco
- Trar
- Envi

Publications

Spatial Units

Perception surveys

Statistics illustrated

Population on 1 January by age groups and sex - cities and greater cities

Title: Population on 1 January by age groups and sex - cities and greater cities

Code: urb_cpop1

Last update of data: 23/05/2019

Last table structure change: 15/04/2019

Number of values: 366311

Data availability - by country:

Code	Label	Oldest data
-	overall	1990

News News releases Release calendar What's new?

Data Database Statistics by theme Statistics A to Z

Publications All publications Statistics Explained

What do you find on Open Data Portals?



HOME DATEN THEMEN ANWENDUNGEN

OpenDataPortal Österreich > Datenkatalog > Datensätze

Organisationen
Für diese Suche wurden keine Organisationen gefunden.

Gruppen
Für diese Suche wurden keine Gruppen gefunden.

Die Daten in unse
ist unter anderen
den einzelnen Da

Leopoldstadt

Keine Datensätze gefunden bei der Suche "Leopoldstadt" Sortieren nach Relevanz



Not too much!

From (Linked) Open Data to Knowledge Graphs

- Needs some more explanation...
- Interlude: ***What is (new) a(bout) Knowledge Graph(s)?***

What is a Knowledge Graph?

- ... good question!

Official Blog
Insights from Googlers into our products, technology, and the Google culture

Introducing the Knowledge Graph: things, not strings

May 16, 2012

Cross-posted on the [Inside Search Blog](#)

Search is a lot about discovery—the basic human need to learn and broaden your horizons. But searching still requires a lot of hard work by you, the user. So today I'm really excited to launch the Knowledge Graph, which will help you discover new information quickly and easily.

Take a query like [taj mahal]. For more than four decades, search has essentially been about matching keywords to queries. To a search engine the words [taj mahal] have been just that—two words.

The screenshot shows a Google search for "taj mahal". The search bar at the top contains "taj mahal" and the search button is highlighted. Below the search bar, the search results are displayed. On the left, there are tabs for "Everything", "Images", "Maps", "Videos", "News", "Shopping", and "More". The "Everything" tab is selected. The search results include a Wikipedia entry for "Taj Mahal", a Wikipedia entry for "Taj Mahal (musician)", and a listing for "Atlantic City New Jersey Casino Hotels | Trump Taj Mahal Atlantic City". On the right side of the search results, there is a "Taj Mahal" knowledge panel. This panel includes a map of the Taj Mahal in Agra, India, a description of the monument, its height (561 feet / 171 m), the year it was opened (1668), its address, architectural style (Mughal architecture), phone number, and architect (Ustad Ahmad Lahauri). Below the knowledge panel, there are sections for "People also search for" and "See results about". The "See results about" section is highlighted with a blue box and contains three items: "Taj Mahal Musician" (Henry Saint Clair Fredericks), "Trump Taj Mahal Casino Resort", and "Taj Mahal".

The announcement says more what a KG **does** than what it **is...**

“[graph of] interesting things and [understanding their] relationships [for search]”

What is a Knowledge Graph? More examples and Definitions:

Other companies with (closed) knowledge graphs:

- [Facebook](#)
- [Bing](#)
- Yandex' Object Answer
- [Baidu](#)
- [LinkedIn](#)
- [Amazon](#)
- [NASA](#)

Some free **open knowledge graphs**:

- [DBpedia](#)
- [WikiData](#)

Some Definitions:

- [McCusker, Chastain, Erickson, and McGuinness. What is a Knowledge Graph?](#) (unpublished, 2016).
 - *“principled” aggregation of **Linked Data**? p.7*
- [Rospocher, van Erp, Vossen, Fokkens, Aldabe, Rigau, Soroa, Ploeger, Bogaard. Building event-centric knowledge graphs from news.](#) JWS (2016)
 - *“knowledge-base of facts about entities typically [Remark: often automatically] obtained from structured repositories [such as Freebase]”*
- [Lisa Ehrlinger and Wolfram Wöß Towards a Definition of Knowledge Graphs \(SEMANTiCS2016\)](#)
 - *“A knowledge graph acquires and integrates information into an ontology and applies a reasoner to derive new knowledge.”*

What is a Knowledge Graph? More examples and Definitions:

Other companies with (closed) knowledge graphs:

- [Facebook](#)
- [Bing](#)
- [Yandex' C](#)
- [Baidu](#)
- [LinkedIn](#)
- [Amazon](#)
- [NASA](#)

Some free c

- [DBpedia](#)
- [WikiData](#)

The screenshot shows the website for Schloss Dagstuhl, Leibniz-Zentrum für Informatik. The main heading is "Knowledge Graphs: New Directions for Knowledge Representation on the Semantic Web" for the seminar on September 9-14, 2018. Organizers listed include Piero Andrea Bonatti (University of Naples, IT), Stefan Decker (RWTH Aachen, DE), Axel Polleres (Wirtschaftsuniversität Wien, AT), and Valentina Presutti (CNR - Rome, IT). A group photo of the seminar participants is shown at the bottom.

Some Definitions:

10 (Re)Defining Knowledge Graphs

Aidan Hogan (IMFD, DCC, University of Chile - Santiago de Chile, CL), Dan Brickley (Google Research - Mountain View, US), Claudio Gutierrez (IMFD, DCC, University of Chile - Santiago de Chile, CL), Axel Polleres (Wirtschaftsuniversität Wien, AT), and Antoine Zimmermann (École des Mines de Saint-Étienne, FR)

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© Aidan Hogan, Dan Brickley, Claudio Gutierrez, Axel Polleres, and Antoine Zimmermann

The phrase “Knowledge Graph” has recently gained a lot of attention in both industry and academia. But what is a “Knowledge Graph”? Several definitions have been proposed but – we shall argue – fall short of capturing the full generality of the usage of the term. We argue for a looser, more permissive definition that may be instantiated in various concrete ways, setting the stage for the study and practice of “Knowledge Graphs” to become a commons that unites – rather than divides – previously disparate areas of Computer Science, focused

We thus propose to define a “Knowledge Graph”, succinctly, as:


- *“a graph of data with the intent to compose knowledge”.*

as nodes, with their relations represented as edges; technically this notion can be instantiated with a number of concrete graph models, including for example:

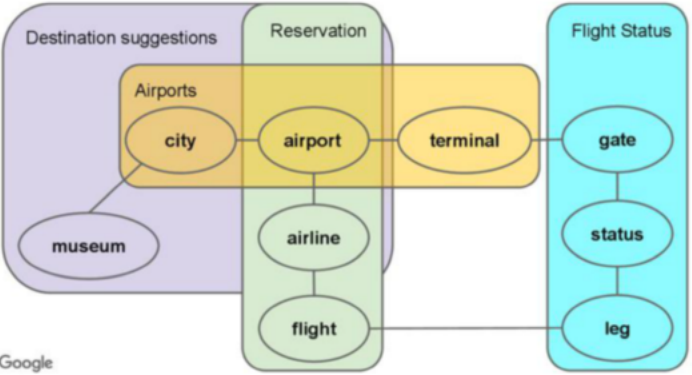
- **directed edge-labelled graphs** (aka sets of triples), composed of named binary relations (labelled edges) between entities (nodes);
- **property graphs**, which extends directed edge-labelled graphs such that both nodes and edges may be additionally annotated with sets of property-attribute pairs;
- **named graphs**, where rather than supposing one large graph, data are represented as a collection of (typically directed edge-labelled) graphs, each associated with an identifier.

What is new/different about Knowledge Graphs?

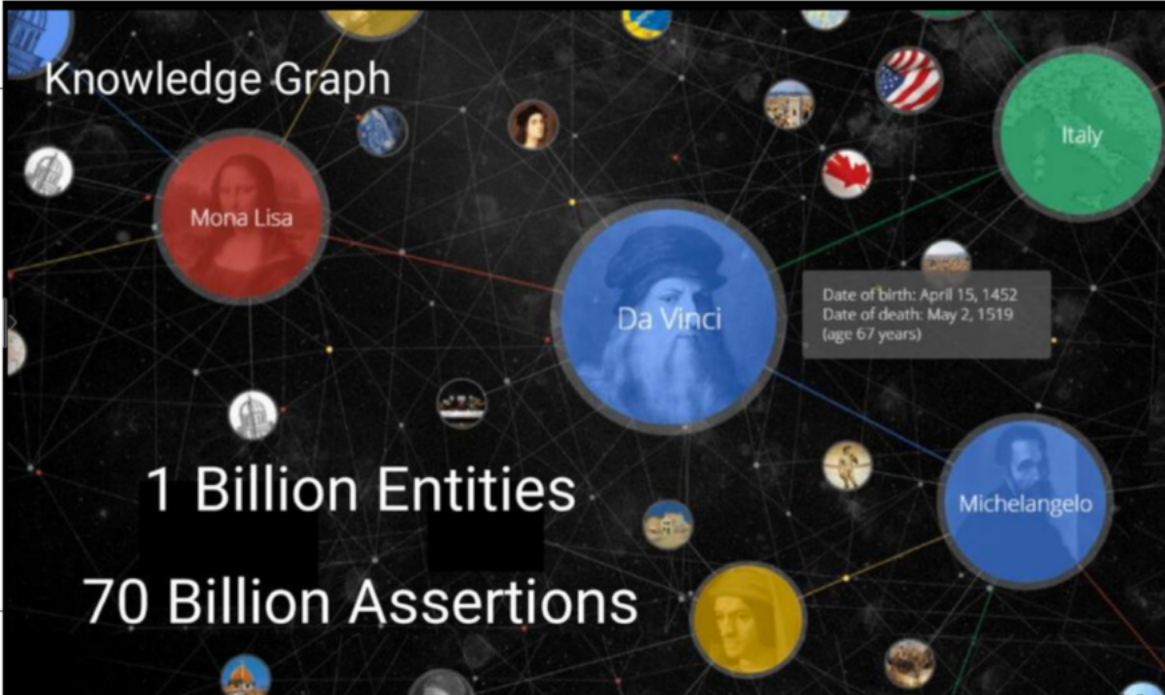
- Jamie Taylor, Google, Inc., Keynote [ISWC2017](#)



The Power of Knowledge Graph: Interlocking data



Google



Knowledge Graph

1 Billion Entities
70 Billion Assertions

- Actors, Directors, Movies
- Art Works & Museums
- Cities & Countries
- Islands, Lakes, Lighthouses
- Music Albums & Music Groups
- Planets & Spacecraft
- Roller Coasters & Skyscrapers
- Sports Teams

[...]

Answer whether (something like) RDF and/or triple stores are used under the hood answered vaguely...

What is new/different about Knowledge Graphs?

- Jamie Taylor, Google, Inc., Keynote [ISWC2017](#)

- We have good reasons to assume that they use similar methods under the hood....

Cautious deductive, rule-based inference, plus *heuristics* on provenance and confidence to avoid non-sensual inferences and resolve inconsistencies works.

What's (probably) new?

statistical methods/learning more central:

- lots of data enables
- more accurate confidence scores
- rule mining (not restricted to OWL)



Answer whether (something like) RDF and/or triple stores are used under the hood answered vaguely...

- We have good reasons to assume that they use similar/ the same methods under the hood...



creator



migratedTo



creator



creator

creator



creator

creator

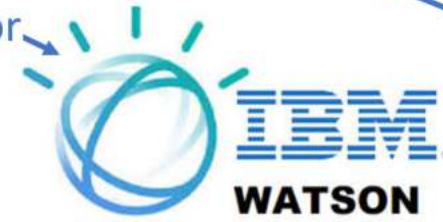


creator



creator

creator



used

- ... and have extended/improved them!




Google

cities in the UK with than 1M people

All Images News Shopping Videos More Settings Tools

About 37.900.000 results (0,55 seconds)

According to citymetric.com



Birmingham... Manchester... Liverpool Sheffield Glasgow

Metropolitan areas

- London – 13,709,000.
- Birmingham-Wolverhampton – 3,683,000.
- Manchester – 2,556,000.
- Leeds-Bradford – 2,302,000.
- Liverpool-Birkenhead – 2,241,000.
- Newcastle-Sunderland – 1,599,000.
- Sheffield – 1,569,000.
- Southampton-Portsmouth – 1,547,000.

Which cities in the UK have more than 1M people?

<http://yasgui.org/short/UVOyhX8ft>

```
PREFIX : <http://dbpedia.org/resource/>
PREFIX dbo: <http://dbpedia.org/ontology/>
PREFIX yago:
<http://dbpedia.org/class/yago/>

SELECT DISTINCT ?city ?pop WHERE {
  ?city a yago:City108524735 .
  ?city dbo:country :United_Kingdom.
  ?city dbo:populationTotal ?pop

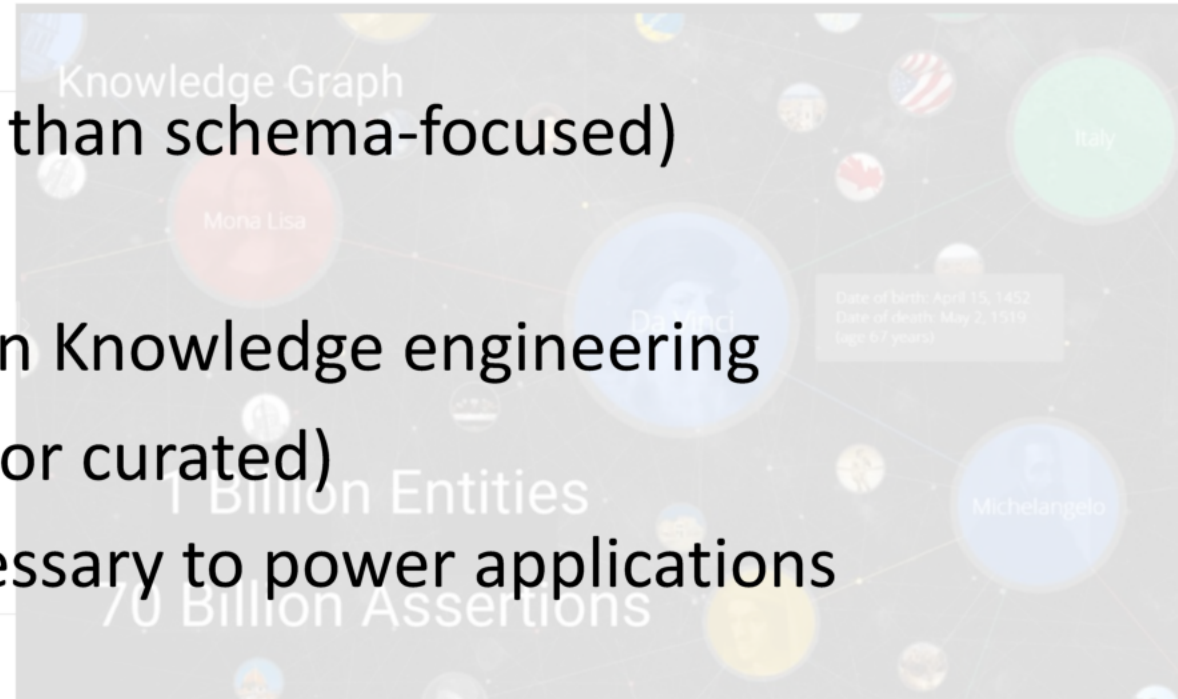
  FILTER ( ?pop > 1000000 )
}
```


Summary:

What is new/different about Knowledge Graphs?

• Jamie Taylor, Google, Inc., Keynote [ISWC2017](#)

- Large-scale (data-focused rather than schema-focused)
- Monolithic, rather than linked
- Knowledge extraction rather than Knowledge engineering
- Collectively created (automated or curated)
- Purpose-driven: knowledge necessary to power applications
- (Logical) consistency not a must



• Actors & Directors
• Art Works & Museums
• Cities & Countries
• Islands, Lakes, Lighthouses

• Planets & Spacecraft
• Roller Coasters & Skyscrapers
• Sports Teams

• **Ontological expressivity** not central – BUT: **Expressing context** is!

Answer whether (something like
RDF and
un

For instance:

- Provenance
- Temporal context
- Confidence

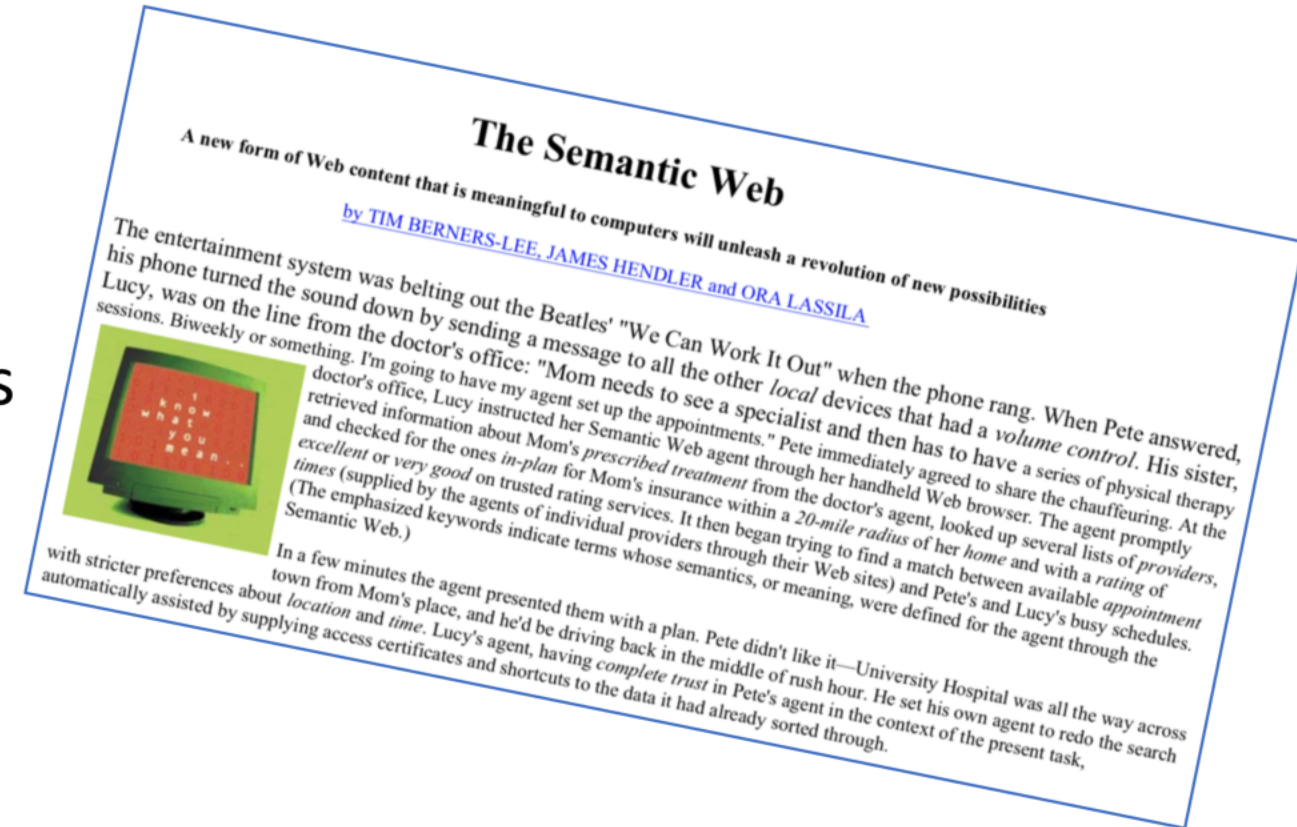
From Knowledge Graphs (back) to Semantic Web

What closed KGs already enable:

- Semantic Search
- Appointment detection in emails
- Ratings of products/services

However,

- most of these KGs and applications are closed
- they often cover either only generic, or domain-specific “knowledge”



From Knowledge Graphs (back) to Linked Open Data:

- *There are also open KGs & They use RDF, SPARQL & Linked Data!*



Wikidata as RDF ... can be queried by SPARQL

- “Simple” surface [query](#):

Which cities in the UK have more than 1M people?

```
SELECT DISTINCT ?city WHERE {  
  ?city wdt:P31/wdt:P279* wd:Q515.  
  ?city wdt:P1082 ?population .  
  ?city wdt:P17 wd:Q38 .  
  FILTER (?population > 1000000) }
```

instance of (P31)
that class of which this subject is a particular example and member. (Subject typically an individual member with Proper Name label.) Different from P279 (subclass of).

subclass of (P279)
all instances of these items are instances of those items; this item is a class (subset) of that item. Not to be confused with Property:P31 (instance of).

city (Q515)
large and permanent human settlement

population (P1082)
number of people inhabiting the place; number of people of subject

country (P17)
sovereign state of this item
United Kingdom (Q145)
country in Europe

- What's this?

From Knowledge Graphs (back) to Linked Open Data:

- Managing context makes things harder! → but is also doable!

- However, Wikidata has more complex info: (temporal context, provenance,...)

Which cities in the UK have reached 1M in which year?

... Can I query that with SPARQL? [Yes!](#)

Wikidata Query Service

```
1
2 SELECT ?city (min(?time) as ?year) WHERE {
3   ?city wdt:P31/wdt:P279* wd:Q515.
4   ?city wdt:P17 wd:Q38 .
5   ?city p:P1082 ?statement .
6   ?statement <http://www.wikidata.org/prop/statement/value/P1082> ?value .
7   ?statement <http://www.wikidata.org/prop/qualifier/P585> ?time .
8   ?value <http://wikiba.se/ontology#quantityAmount> ?population .
9   FILTER (?population > 1000000 )
10  } GROUP BY ?city
```

population	point in time	determination method
8,416,535±0	2012	estimation
1,011,157±0	1801	census
	1811	census

http://www.visionofbritain.org.uk/data_cube_page.jsp?data_theme=T_POP&data_cube=N_TOT_POP&u_id=10097836&c_id=10001043&add=N

BTW, seemingly not yet doable in Google

Which cities in the UK have reached 1M in which year?



From Knowledge Graphs (back) to Linked Open Data:

- *(Open) Knowledge Graphs can be used to link Open Data!*

Recall: What do you find on Open Data Portals?



odp
OPEN DATA PORTAL
ÖSTERREICH
All you can Data

HOME DATEN THEMEN ANWENDUNGEN

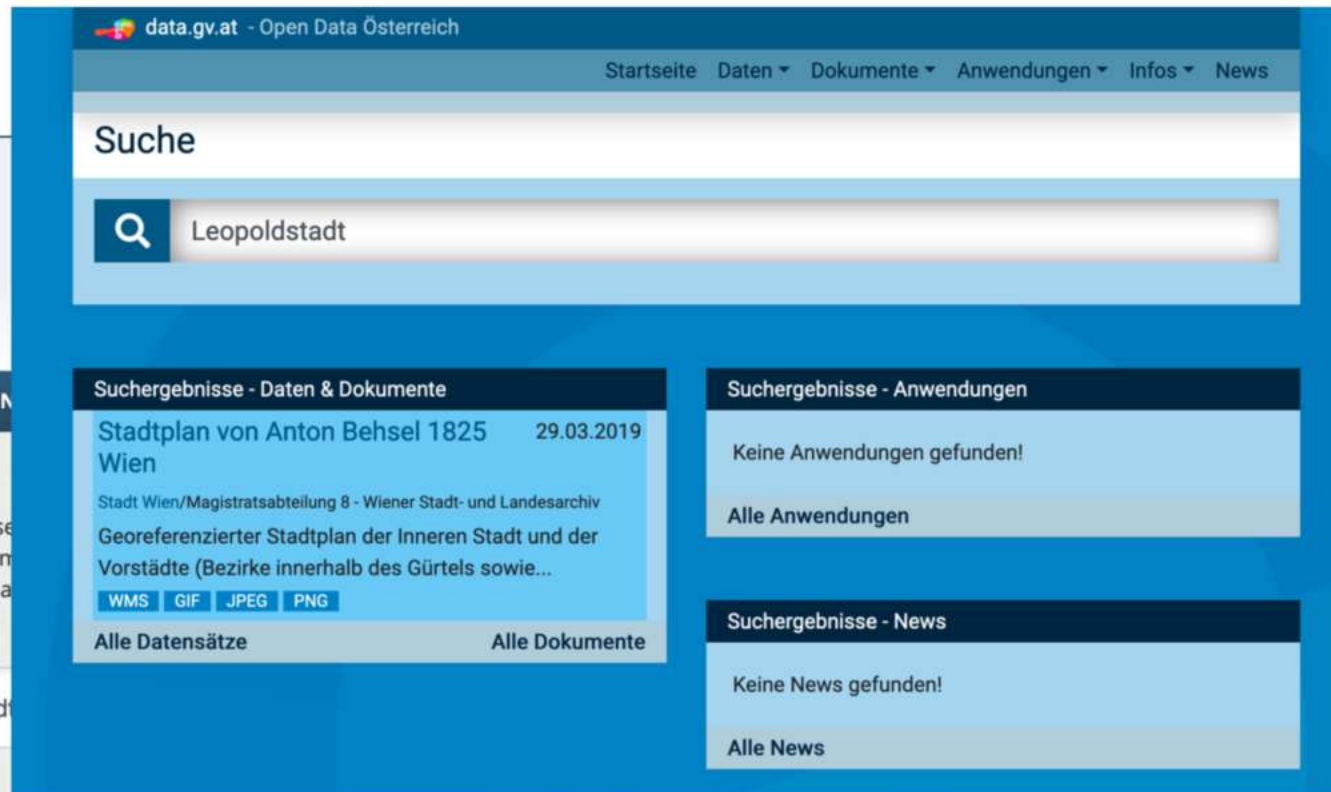
OpenDataPortal Österreich > Datenkatalog > Datensätze

Organisationen

Für diese Suche wurden keine Organisationen gefunden.

Gruppen

Für diese Suche wurden keine Gruppen gefunden.



data.gv.at - Open Data Österreich

Startseite Daten Dokumente Anwendungen Infos News

Suche

Leopoldstadt

Suchergebnisse - Daten & Dokumente

Stadtplan von Anton Behsel 1825 29.03.2019
Wien

Stadt Wien/Magistratsabteilung 8 - Wiener Stadt- und Landesarchiv
Georeferenzierter Stadtplan der Inneren Stadt und der Vorstädte (Bezirke innerhalb des Gürtels sowie...)

WMS GIF JPEG PNG

Alle Datensätze Alle Dokumente

Suchergebnisse - Anwendungen

Keine Anwendungen gefunden!

Alle Anwendungen

Suchergebnisse - News

Keine News gefunden!

Alle News



Not too much!

Keine Datensätze gefunden bei der Suche "Leopoldstadt"

Sortieren nach Relevanz

From Knowledge Graphs (back) to Linked Open Data:

- (Open) Knowledge Graphs can be used to link Open Data!

Google Dataset Search: Building a search engine for datasets in an open Web ecosystem

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Mountain View, California

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Dan Brickley
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The screenshot shows the Google Dataset Search interface. At the top, it says "Google Dataset Search Beta" and "schema.org". The search query is "Leopoldstadt". Below the search bar, it indicates "16 results found". The first result is from "statista" and is titled "Mitarbeiter der Erste Group nach Ländern 2018". The result card includes a blue button that says "Explore at de.statista.com". To the right of the result card, there are details: "Dataset provided by Statista", "Time period covered 2018", "Area covered Österreich", and "Description". The description text is partially visible at the bottom: "Die Statistik zeigt die Anzahl der Mitarbeiter der Erste Group nach Ländern im Jahr 2018. Die Erste Group Bank AG wurde im Jahr 1819 in der Leopoldstadt, einer Vorstadt Wiens, als 'Erste österreichische Spar-Casse' gegründet. Heute ist sie eine der größten Bankengruppen in Zentral- und"



A good start, but not much better either!

From Knowledge Graphs (back) to Linked Open Data:

- (Open) Knowledge Graphs can be used to link Open Data!

Google Dataset Search: Building a search engine for datasets in an open Web ecosystem

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Dan Brickley
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Google
Mountain View, California

Google Dataset Search Beta

Search for Datasets

schema.org



A good start, but not much better either!

Department of Housing and Urban Development / US Department of Housing and Urban Development

Housing Affordability Data System (HADS)

Metadata Updated: March 8, 2017

The Housing Affordability Data System (HADS) is a set of files derived from the 1985 American Housing Survey (AHS) and the 2002 and later Metro AHS. This system categorizes affordability and households by income, with respect to the Adjusted Median Income (AMI), and poverty income. It also includes housing cost burden for owner and renter households. The data has been the basis for the worst case needs tables since 2001. The tables are available since they were derived from AHS public use files and the resulting income limits and give the community of housing analysts the opportunity to use a consistent set of affordable housing data.

Access & Use Information

- Public: This dataset is intended for public access and use.
- License: No license information was provided. If this work was prepared by an organization, you should check with the organization for more information.

data.gv.at

Katalog Bildungsausgaben

Bildungsausgaben; Regionale Gliederung; Bildungseinrichtung

Daten und Ressourcen

ÖGD bildungsausgaben BilDAUS 1

Veröffentlichende Organisation bzw. Person: Statistik Austria

eurostat

Your key to European statistics

European Commission > Eurostat > Cities (Urban Audit) > Database

City statistics (urb)

- Cities and greater cities (urb_cgc)
- Population on 1 January by age groups and sex - cities and greater cities (urb_cpopsr)
- Population structure - cities and greater cities (urb_cpopsr)
- Population by citizenship and country of birth - cities and greater cities (urb_cpopsr)
- Fert
- Liv
- Edu
- Cult
- Lab
- Eco
- Tran
- Env

Population on 1 January by age groups and sex - cities and greater cities (urb_cpopsr)

Title: Population on 1 January by age groups and sex - cities and greater cities (urb_cpopsr)

Code: urb_cpopsr

Last update: 2016-03-10

Can we do better (using KGs)?

From Knowledge Graphs (back) to Linked Open Data:



- *Open Knowledge Graphs can be used to link Open Data!*

Example Open Data Table:

<i>federal state</i>	<i>district</i>	<i>year</i>	<i>sex</i>	<i>population</i>
Upper Austria	Linz	2013	male	98157
Upper Austria	Steyr	2013	male	18763
Upper Austria	Wels	2013	male	29730
...

From Knowledge Graphs (back) to Linked Open Data:



- *Open Knowledge Graphs can be used to link Open Data!*

Open Data CSVs look more like this

<i>NUTS2</i>	<i>LAU2_NAME</i>	<i>YEAR</i>	<i>SEX</i>	<i>P_TOTAL</i>
AT31	Linz	2013	1	98157
AT31	Steyr	2013	1	18763
AT31	Wels	2013	1	29730
...

From Knowledge Graphs (back) to Linked Open Data:



- *Open Knowledge Graphs can be used to link Open Data!*

What can we do to make Open Data better searchable?

- Particularly **temporal** and **geospatial** search requires better support [2]

<i>NUTS2</i>	<i>LAU2_NAME</i>	<i>YEAR</i>	<i>SEX</i>	<i>AGE_TOTAL</i>
AT31	Linz	2013	1	98157
AT31	Steyr	2013	1	18763
AT31	Wels	2013	1	29730
...

From Knowledge Graphs (back) to Linked Open Data:



- *Open Knowledge Graphs can be used to link Open Data!*

Geospatial Linked Data:

Stanford 23 m
P PPL populated place 5398563
United States US » California CA » Santa Clara 085
population : 13809
37.42411, -122.16608
N 37°25'27" W 122°09'58"
geotree .kml .rdf

Stanford University
ESCONDIDO VILLAGE
EVERGREEN PARK
COLLEGE TERRACE

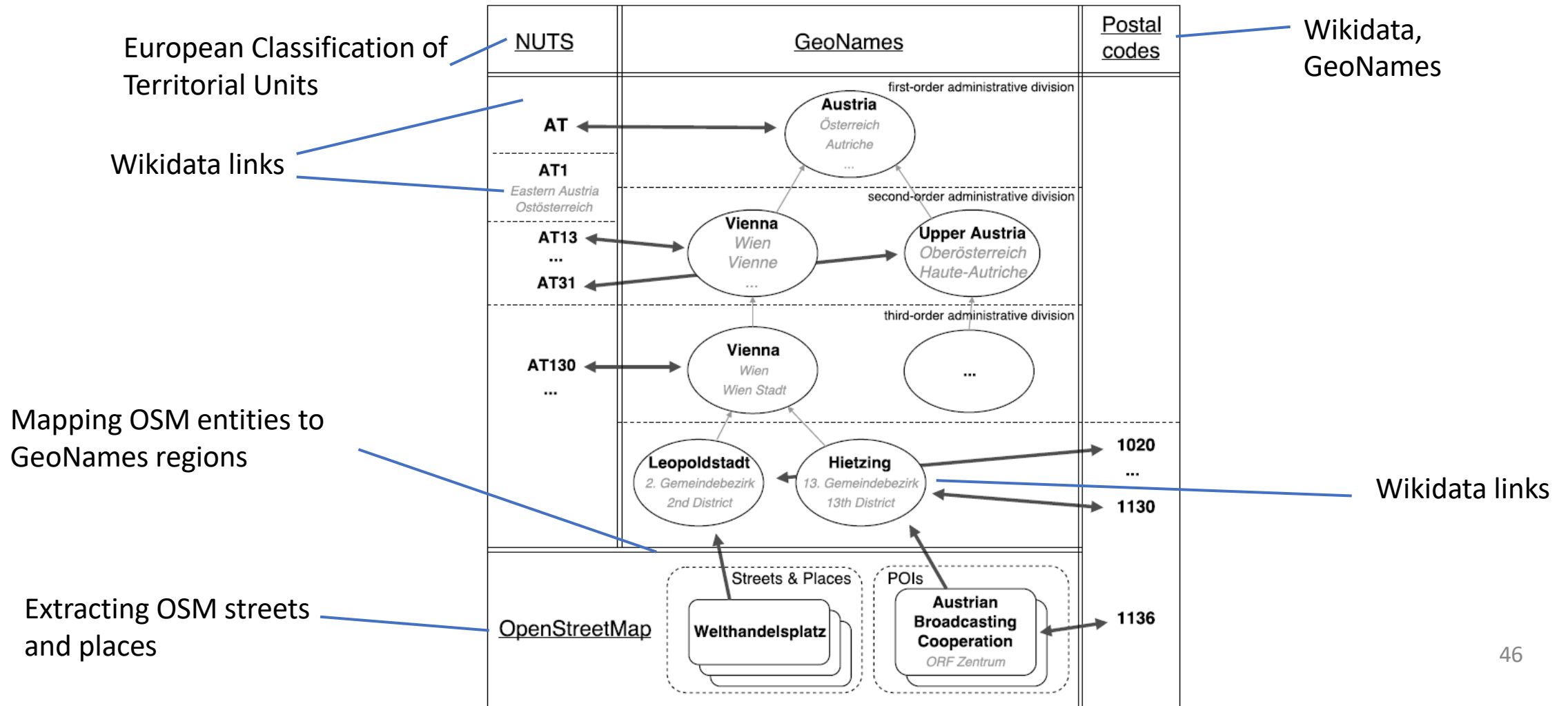
Richard M. Lucas Center for Imaging
Health Research and Policy Redwood Building
Medical School Office Building
School of Medicine Loading
Welch Road
Pasteur Drive
Governor's Lane
Jordan Way
Campus Drive West
Campus Drive



From Knowledge Graphs (back) to Linked Open Data:



- *Open Knowledge Graphs can be used to link Open Data!*



From Knowledge Graphs (back) to Linked Open Data:

- *Open Knowledge Graphs can be used to link Open Data!*

How well does it work? Indexed Datasets

<u>portal</u>	<u>datasets</u>	<u>CSVs</u>	<u>indexed</u>
<i>total</i>			15728
govdata.de	19464	10006	5646
data.gv.at	20799	18283	2791
offenedaten.de	28372	4961	2530
datos.gob.es	17132	8809	1275
data.gov.ie	6215	1194	884
data.overheid.nl	12283	1603	828
data.gov.uk	44513	7814	594
data.gov.gr	6648	414	496
data.gov.sk	1402	877	384
www.data.gouv.fr	28401	6038	258
opingogn.is	54	49	41

From Knowledge Graphs (back) to Linked Open Data:

- *Open Knowledge Graphs can be used to link Open Data!*

Search Interface:

<https://data.wu.ac.at/odgraphsearch/>

Faceted query interface:

- Timespan
- Time pattern
- Geo-entities
- Full-text queries
- SPARQL endpoint

Back end:

- **MongoDB** for efficient key look-ups
- **ElasticSearch** for indexing and full-text queries
- **Virtuoso** as a triple store

Temporal filters

Filter results by timespan: Off Title & description CSV columns

1/2010 1/2020

Filter pattern

Apply Filter

Linz

Republic of Austria > Oberösterreich > Linz Stadt > Linz

Spatial entity or Full-text results

Hotspot - Standorte - Hotspot Standorte [↗](#) Stadt Linz <http://data.gv.at>
POI's (Points of Interest) für Hotspot (freies, kostenloses WiFi) in der Stadt Linz. Die Koordinaten sind im im EPSG-Codes WGS84 verfügbar.

Nummer	Latitude	Longitude	Name	Kurztext	Start im Jahr	Ende im Jahr	Stadt	Postleitzahl
4007	48,304793	14,299414	Hotspot Linz - Rotes...	Hier ist nur einer v...	2013	0	Linz	4020

Finanzgebarung der Gemeinden in Oberösterreich - Oö. Gemeinde- [↗](#) Land Oberösterreich <http://data.gv.at>
Finanzgebarung 2015 [↗](#)
Finanzdaten der 444 oberösterreichischen Gemeinden

Jahr	NUTS2	Gemeindenummer	Gemeindenname	Ordentliche Einnahme...	Ordentliche Ausgaben	Außere Einnahr
2015	AT31	40101	Linz	628704196,3	718773006,9	131859

From Knowledge Graphs (back) to Linked Open Data:

- *Open Knowledge Graphs can be used to link Open Data!*

Lessons learned

- Geospatial and Temporal scope is the most useful search feature for Open Data
- Respective Hierarchical Knowledge Graphs can be built from existing Linked Data Sources
- Our algorithms annotate CSV tables **and** their metadata descriptions

→ **KGs improve search (with some extra work)**

- *Plus: RDF and SPARQL allow us to build application-specific KGs as “principled” aggregation(s) of **Linked Data**’ (cf. Def. slide 29)*



First Look
Journal of Web Semantics

Enabling Spatio-Temporal Search in Open Data

JWS: Information Retrieval

23 Pages • Posted: 20 Dec 2018 • First Look: Accepted

[Sebastian Neumaier](#)

Vienna University of Economics and Business; Vienna University of Technology

[Axel Polleres](#)

Vienna University of Economics and Business; Complexity Science Hub Vienna; Stanford University

Abstract

Intuitively, most datasets found on governmental Open Data portals are organized by spatio-temporal criteria, that is, single datasets provide data for a certain region, valid for a certain time period. Likewise, for many use cases (such as, for instance, data journalism and fact checking) a pre-dominant need is to scope down the relevant datasets to a particular period or region. Rich spatio-temporal annotations are therefore a crucial need to enable semantic search for (and across) Open Data portals along those dimensions, yet - to the best of our knowledge - no working solution exists. To this end, we (i) present a scalable approach to construct a spatio-temporal knowledge graph that hierarchically structures geographical as well as temporal entities, (ii) annotate a large corpus of tabular datasets from open data portals with entities from this knowledge graph, and (iii) enable structured, spatio-temporal search and querying over Open Data catalogs, both via a search interface as well as via a SPARQL endpoint, available at data.wu.ac.at/odgraphsearch/.

Keywords: open data, spatio-temporal labelling, spatio-temporal knowledge graph

Suggested Citation:

Neumaier, Sebastian and Polleres, Axel, Enabling Spatio-Temporal Search in Open Data (December 20, 2018). Available at SSRN: <https://ssrn.com/abstract=3304721> or <http://dx.doi.org/10.2139/ssrn.3304721>

From Knowledge Graphs (back) to Linked Open Data:



- *Open Knowledge Graphs can be used to link Open Data!*

How can we also use numeric values?

<i>NUTS2</i>	<i>LAU2_NAME</i>	<i>YEAR</i>	<i>SEX</i>	<i>P_TOTAL</i>
AT31	Linz	2013	1	98157
AT31	Steyr	2013	1	18763
AT31	Wels	2013	1	29730
...

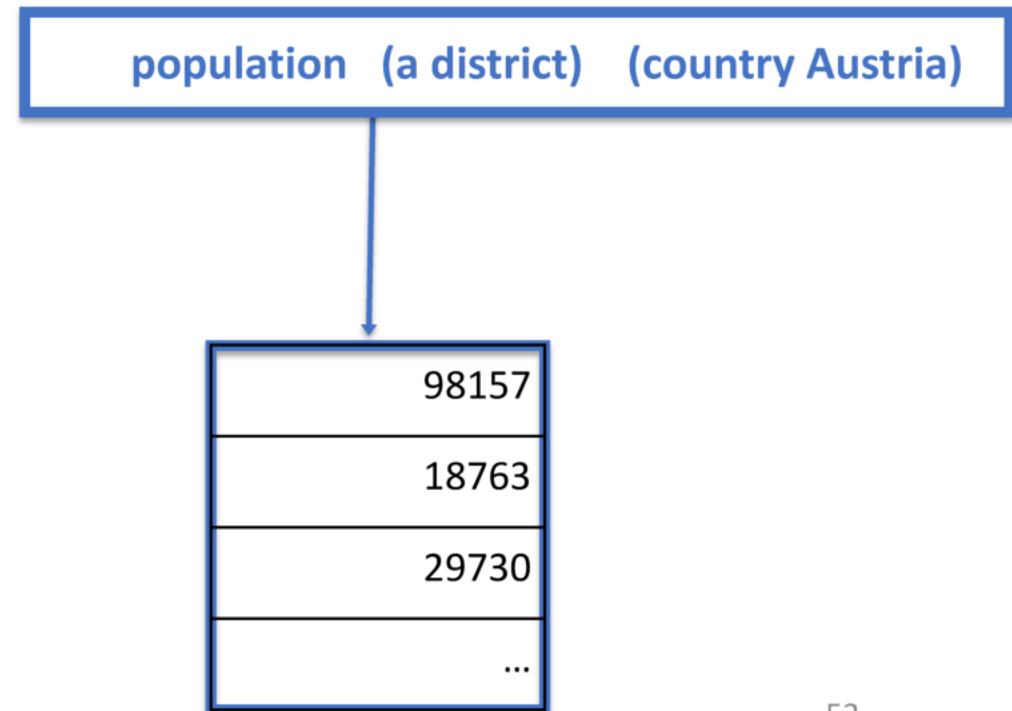
From Knowledge Graphs (back) to Linked Open Data:



- *Open Knowledge Graphs can be used to link Open Data!*

How can we also use numeric values?

- Identifying the most likely semantic label for a bag of numerical values
- Deliberately ignore surroundings
- Map to labels from a KG



From Knowledge Graphs (back) to Linked Open Data:



- *Open Knowledge Graphs can be used to link Open Data!*

Numeric Values in Open KGs?



What's in DBpedia?

- Cities
 - **Population**
 - **Area**
 - Country
 - Location (**Coordinates**)
 - Economic indicators
 - ...
- Organisations:
 - **Revenues**
 - Board members
 - ...
- Persons (e.g. celebrities, sports)
 - Name
 - Profession
 - **Height**
- Landmarks (e.g. famous buildings)
 - **Country**
 - **Location**
 - **Height**
- Events
 - **Dates**
 - **Location**

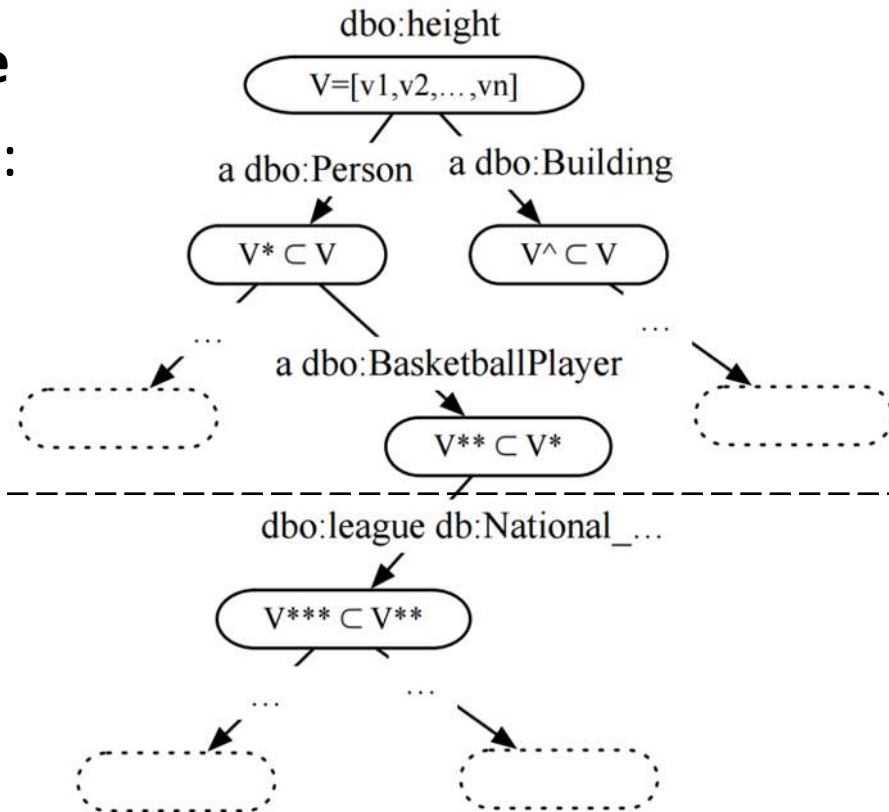


From Knowledge Graphs (back) to Linked Open Data:

- *Open Knowledge Graphs can be used to link Open Data!*

Background Knowledge Graph

- properties with **numerical range**
- Hierarchical clustering approach:
- Two hierarchical layers:
 - **Type** hierarchy (using OWL classes)
 - **Property-object** hierarchy (shared property-object pairs)

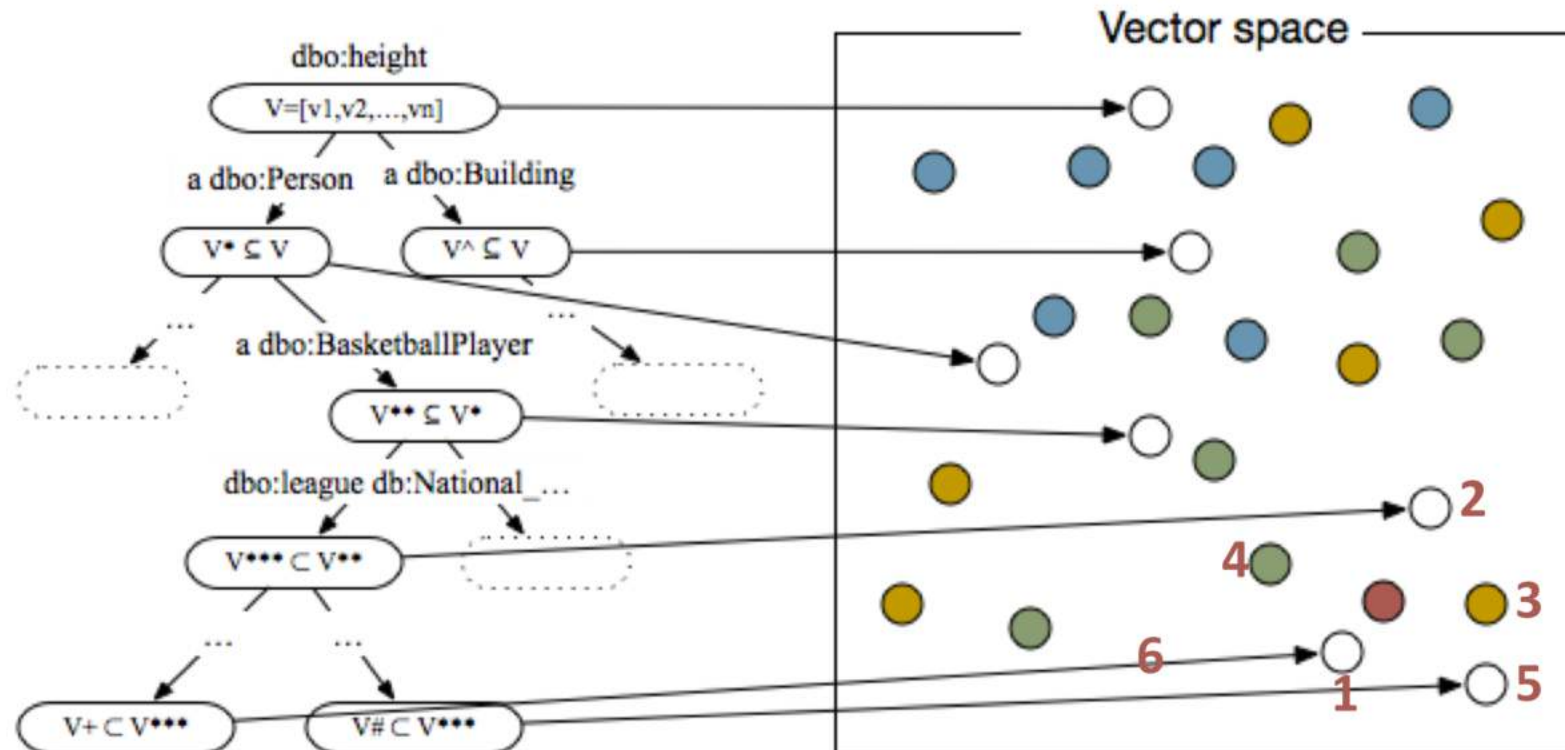




From Knowledge Graphs (back) to Linked Open Data:

- *Open Knowledge Graphs can be used to link Open Data!*

Label based on Nearest Neighbors



From Knowledge Graphs (back) to Linked Open Data:



- *Open Knowledge Graphs can be used to link Open Data!*
- *Open KGs don't/only partially cover Knowledge in Open Data!*

Example Labelling:

populationTotal (a Settlement)
populationDensity (a City)

NUTS1	NUTS2	NUTS3	DISTRICT_CODE	T	WV	WK	BZ	SPR	WBER	ABG.	UNG.	OEVP	SPOE	FPOE	GRUE	BZOE	NEOS
AT1	AT13	AT130		1	9	0	0	0	1163061	503284	9386	81974	136391	89963	103249	1516	44891
AT1	AT13	AT130		2	9	1	0	0	111279	52674	774	9344	12395	6482	14154	114	5412
AT1	AT13	AT130		2	9	2	0	0	98379	51785	646	10324	10236	4700	15398	124	6569
AT1	AT13	AT130		2	9	3	0	0	110527	45483	810	5317	13304	7816	10944	115	3613
AT1	AT13	AT130		2	9	4	0	0	229521	84387	1953	10097	27922	21091	11631	256	5299
AT1	AT13	AT130		2	9	5	0	0	212262	97755	1806	18703	25314	16613	19333	324	9175
AT1	AT13	AT130		2	9	6	0	0	175288	82790	1321	17560	19059	11765	18996	242	8389
AT1	AT13	AT130		2	9	7	0	0	225805	88410	2076	10629	28161	21496	12793	341	6434
AT1	AT13	AT130	90301	3	9	1	3	0	57528	27320	412	4938	6586	3567	6969	68	2789
AT1	AT13	AT130	90401	3	9	1	4	0	21000	11027	138	2401	2253	1068	3082	26	1277
AT1	AT13	AT130	90501	3	9	1	5	0	32751	14327	224	2005	3556	1847	4103	20	1346

From Knowledge Graphs (back) to Linked Open Data:



- *Open Knowledge Graphs can be used to **link Open Data!***
- *Open KGs don't/only partially cover Knowledge in Open Data!*

Lessons learned:

- We can assign fine-grained semantic labels
 - **if there is enough evidence in Background Knowledge Graph**
- *However:* Missing domain knowledge for labelling OD

Future work:

- Complementary to existing approaches (column header labeling, entity linking and relation extraction)
- Combined approaches may improve results

International Semantic Web conference 2016:

Multi-level semantic labelling of numerical values

Sebastian Neumaier¹, Jürgen Umbrich¹, Josiane Xavier Parreira², and Axel Polleres¹

¹ Vienna University of Economics and Business, Vienna, Austria

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Abstract. With the success of Open Data a huge amount of tabular data sources became available that could potentially be mapped and linked into the Web of (Linked) Data. Most existing approaches to “semantically label” such tabular

The journey doesn't end here...

Open Knowledge Graphs can be used for many other AI applications!

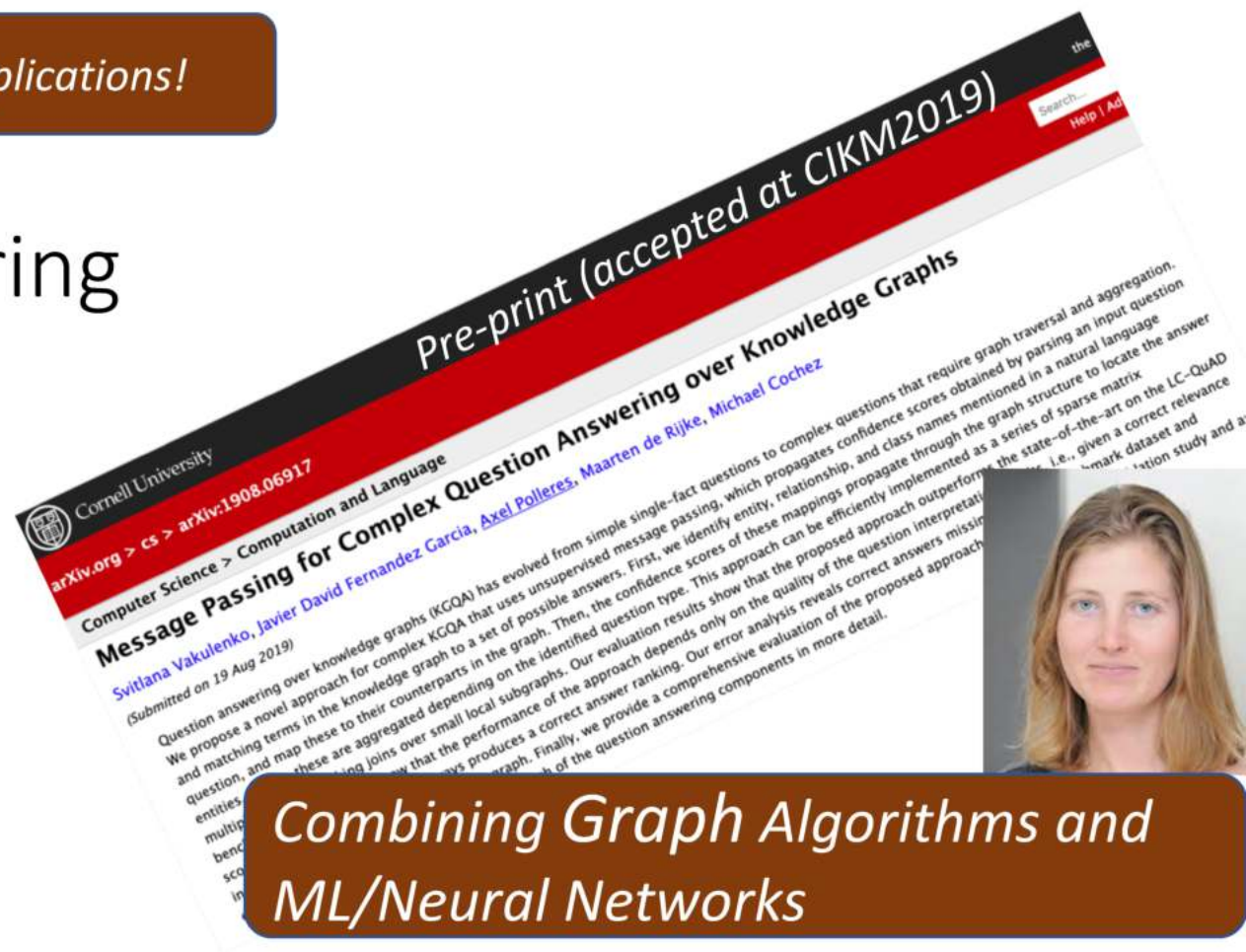
E.g. Open KG Question Answering



creator



used



Combining Graph Algorithms and ML/Neural Networks

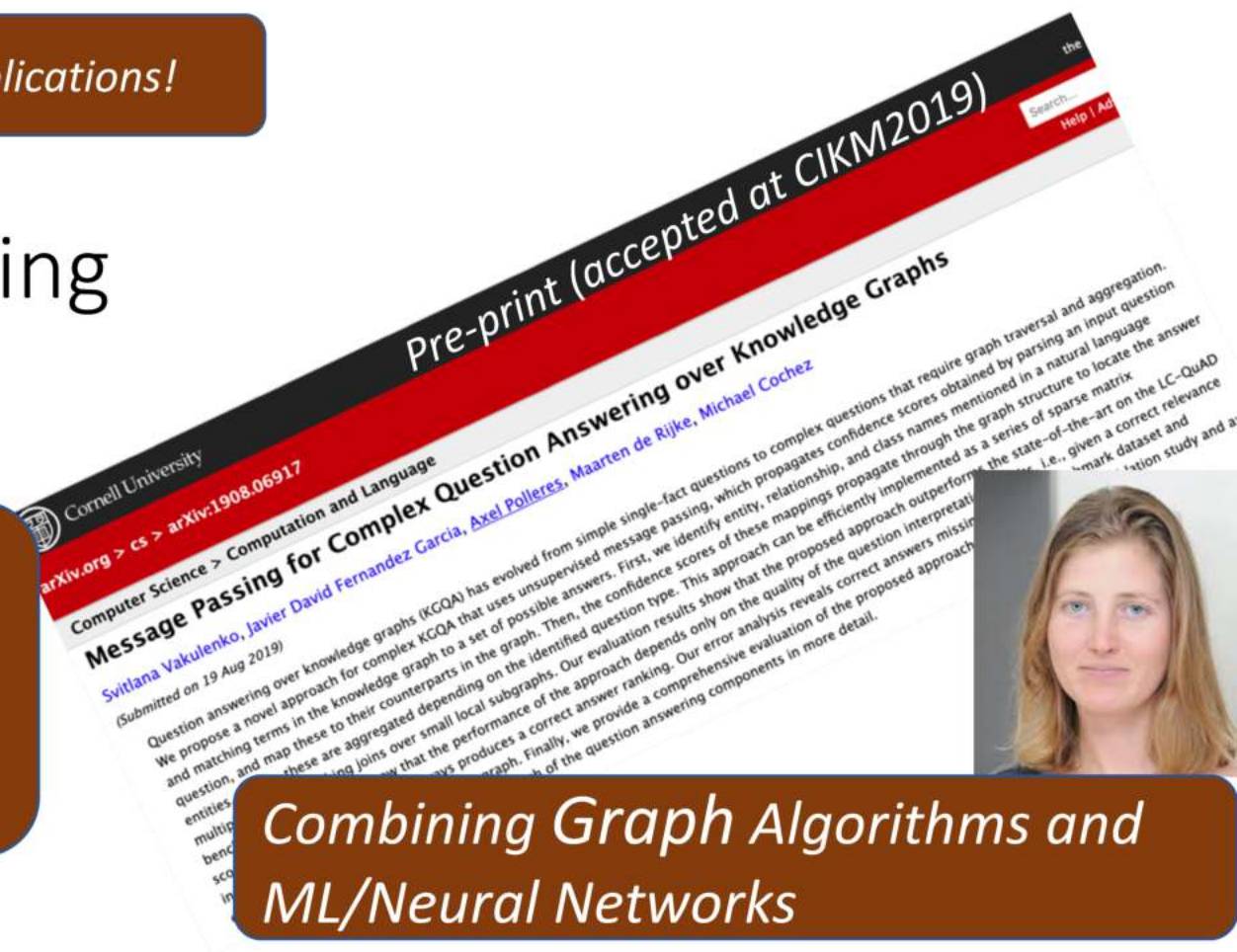
The journey doesn't end here...

Open Knowledge Graphs can be used for many other AI applications!

E.g. Open KG Question Answering

More examples of active research topics:

- *Using ML/NN for KG population/extraction*
- *Graph embeddings for automated KG enrichment/repair*



Last but not least, some bad news...

Bad news: Decentralized Open KGs are hard to maintain and serve

- Hosting federated SPARQL endpoints is (too) expensive
- Many Linked Data datasets are not maintained sustainably.
- Linked Datasets difficult to crawl and process automatically

Actually: Good news!

Still more research needed and actively being conducted!

Examples:

- *Federated SPARQL querying*
- *Client-Server Load-Balancing (LDF, SAGE, etc.)*
- *Efficient/lightweight triple stores (e.g. HDT)*
- *Graph Databases in the Cloud*
- *Automated Linked Data Quality checking*
- *(BTW, real applications often also need access-control, policies)*

A More Decentralized Vision for Linked Data

Axel Polleres^{1,2}, Maulik R. Kamdar¹, Javier D. Fernández², Tania Tudorache¹, and Mark A. Musen¹

¹ Stanford University, CA, USA

² Vienna Univ. of Economics & Business / Complexity Science Hub Vienna, Austria

Abstract. We claim that ten years into Linked Data there are still many unresolved challenges towards arriving at a truly machine-readable *and* decentralized Web of data. With a focus on the the biomedical domain—currently, one of the most promising “adopters” of Linked Data, we highlight and exemplify key technical and non-technical challenges to the success of Linked Data, and we outline potential solution strategies.

DESEMWEB 2018

Time for a postcard...



Time for a postcard...

RDF, Ontologies, Linked Data are a solid basis for Knowledge graphs.

Focus has shifted from schema-centric to data-centric.

Focus has shifted from knowledge engineering to knowledge extraction.

For companies thinking about investing in KGs it makes sense to invest in open, standard technologies for KGs.

Hybrid Reasoning needed (rules + heuristics + inductive/statistical inference (ML))

It is not enough to rely on centralized/closed KGs!

Looking forward to the onward journey!
lot of research left to be done in this space (decentralization, contextualization, federation)!



Confirmed by yesterday's keynote:

Take-home Messages

Future of AI Research for Manufacturing

- **AI provides just sets of methods – the human centric complex solutions should be built upon them – three key research areas for future AI research** (Catalyst & AAAI report):
 - **Integrated intelligence:** combining modular AI capabilities, functionalities and skills, ability to contextualize general capabilities to suit specific uses, creation of open shared knowledge repositories, models of human cognition
 - **Meaningful interaction:** productive collaboration in mixed teams of humans and machines, combining diverse communication modalities (verbal, visual, emotional) while respecting privacy, responsible and trustworthy behaviors
 - **Self-aware learning:** developing robust and trustworthy learning, learning from small amounts of data, incorporating prior knowledge into learning, and learning real-time behaviors for intentional sensing and acting.



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