ONTOLOGIES FOR KNOWLEDGE GRAPHS?

Markus Krötzsch†

reporting on joint work with Stefan Bischoff, Fredo Erxleben, Michael Günther, Maximilian Marx†, Julian Mendez, Ana Ozaki†, Axel Polleres, Sebastian Rudolph, Veronika Thost†, and Denny Vrandečić

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TU Dresden

DL Workshop 2017
2012: The Knowledge Graph

"... one of the key breakthroughs behind the future of search"

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Ontologies for Knowledge Graphs?

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What is a Knowledge Graph?

More than “a database used in an AI application”?

Characteristics of today’s KGs:

- Normalised: Data decomposed into small units (“edges”)
- Connected: Knowledge represented by relationships between these units
- Annotated: Enriched with contextual information to record meta-data and auxiliary details

Typical for many KG applications

Often comes with a promise of declarative processing
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Summary

Knowledge graphs

- introduce graph-based data models
- requiring declarative analytics
- that make non-local connections
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Symbolic KR is the key technology in modern data management especially in AI applications.
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Not really happening

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A Free Knowledge Graph

**Wikidata**

- Wikipedia’s knowledge graph
- Free, community-built database
- Large graph
  (July 2017: >165M statements on >29M entities)
- Large, active community
  (July 2017: >175,000 logged-in human editors)
- Many applications

Freely available, relevant, and active knowledge graph

[Vrandečić & K; Comm. ACM 2014]
I’m in ur phone . . .

Who is Grover Cleveland

Tap to Edit

OK. Check it out:

Grover Cleveland
22nd and 24th president of the United States

Stephen Grover Cleveland was an American politician and lawyer who was the 22nd and 24th President of the United States. He won the popular vote for three presidential elections — in 1884, 1888, and 1892 — and was one of two Democrats to be elected president during the era of Republican political domination dating from 1861 to 1933. He was also the first and to date only President in American history to serve two non-consecutive terms in office.

See More on Wikipedia

Date of birth
March 18, 1837

Birthplace
Caldwell

Date of death
June 24, 1908

Deathplace
Princeton
Tim Berners-Lee (Q80)

British computer scientist

TimBL | Sir Tim Berners-Lee | Timothy John Berners-Lee | TBL | Tim Berners Lee | T. Berners-Lee | T Berners-Lee | Tim Berners-Lee | T.J. Berners-Lee
Tim Berners-Lee (Q80)

British computer scientist

instance of human

employer CERN
start time 1984
end time 1994
position held Fellow

award received Queen Elizabeth Prize for Engineering
point in time 2013
together with Robert Kahn Vint Cerf Louis Pouzin Marc Andreessen

1 reference
Elizabeth Taylor (Q34851)
Elizabeth Rosemond Taylor | Liz Taylor | Dame Elizabeth Rosemond Taylor
British-American actress

instance of: Elizabeth Taylor is a(n) human

Fig.: Taylor standing in multiple relations; from https://tools.wmflabs.org/sqid/#/view?id=Q34851
### Wikidata Statements in Terms of Graphs

#### Elizabeth Taylor (Q34851)

<table>
<thead>
<tr>
<th>spouse</th>
<th>Richard Burton</th>
</tr>
</thead>
<tbody>
<tr>
<td>start time</td>
<td>10 October 1975</td>
</tr>
<tr>
<td>end time</td>
<td>29 July 1976</td>
</tr>
</tbody>
</table>
“Property Graph”: Taylor → Burton

spouse

start time: 1975-10-10
end time: 1976-07-29
Wikidata Statements in Terms of Graphs

“Property Graph”:

```
Taylor --- spouse --- Burton

start time: 1975-10-10
end time: 1976-07-29
```

“RDF”:

```
Taylor --- spouse_in --- ⊙

start time: 1975-10-10

⊙ --- spouse_out --- Burton

end time: 1976-07-29
```
Ontological Modelling in Wikidata

- Classification
  - 25,298,346 instance of statements (for 84.9% of entities)
  - 2,056,181 subclass of statements (for 4.5% of entities)

- Property characteristics/constraints
  - symmetric property (17 instances)
  - transitive property (8 instances)
  - 12,595 statements specifying other constraints (domain, range, disjointness, ...)

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Queries on Wikidata

**SPARQL query service:** [https://query.wikidata.org](https://query.wikidata.org)

- officially maintained, live data
- based on RDF mapping [Erxleben et al., ISWC 2014]
- heavily used: 60M–135M queries per month

---

```
#Inventors killed by their own invention

SELECT ?inventor ?inventorLabel ?gadget ?gadgetLabel WHERE {
  SERVICE wikibase:label { bd:serviceParam wikibase:language "en". }
}
```
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**Initial analysis** of the non-public logs:
- ≤1% queries from human traffic (400–500K per month)
- ≥99% service calls from tools and robots
- Irregular distributions and biases – hard to analyse
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Property paths used for transitivity reasoning
- used in about 50% of human subclass-of queries (20K)
- over 500K queries with subclass-of paths overall
  
  (statistics for May 2017)
OBQA via SPARQL

SPARQL is actually powerful enough for OWL QL reasoning [Bischoff et al., ISWC 2014]

... but the queries then are getting lengthy ...

\[
x \text{ (sCO | eqC | } \text{ {eqC | inte|List|Member | owl:someValuesFrom |}
\text{(owl:onProperty / (INV | SpoEOP)* / } \text{ (~owl:onProperty | rdfs:domain | rdfs:range))}^* \text{ )} \text{ } ?C . }
\{ ?C \text{ subClassOf owl:Nothing} \} \text{ UNION }
\{ ?C \text{ subClassOf } ?D1 \{ \{ ?C \text{ subClassOf } ?D2 \} \text{ UNION univClass[?D2]} \} \}
\{ ?D1 \text{ disjointClasses } ?D2 \} \text{ UNION }
\{ ?V \text{ rdf:type owl:AllDisjointClasses . twoMembers[?V, ?D1, ?D2]} \}
\}
\text{ UNION }
\{ ?C \text{ (owl:onProperty / (INV | SpoEOP)*) } ?P . }
\{ ?P \text{ subPropertyOf owl:bottomObjectProperty} \} \text{ UNION }
\{ ?P \text{ subPropertyOf } ?Q1 \{ \{ ?P \text{ subPropertyOf } ?Q2 \} \text{ UNION univProperty[?Q2]} \}
\{ ?Q1 \text{ (owl:propertyDisjointWith | ~owl:propertyDisjointWith) } ?Q2 \} \text{ UNION }
\{ ?V \text{ rdf:type owl:AllDisjointProperties . twoMembers[?V, ?Q1, ?Q2]} \}
\}
\}
\]

Fig.: A query that checks if \( x \) is equivalent to \( \bot \) (abbreviated)
Beyond OWL QL

**SPARQL cannot support arbitrary OWL reasoning:**

- computing power limited by data complexity
- SPARQL can only perform reasoning in NL
Beyond OWL QL

**SPARQL cannot support arbitrary OWL reasoning:**
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**Queries with higher data complexities?**
- Datalog: PTime-complete data complexity
- Datalog can be used for “query-based” EL reasoning
[K, IJCAI 2011]
Beyond OWL QL

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**Queries with higher data complexities?**
- Datalog: PTime-complete data complexity
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[K, IJCAI 2011]

---

**Query-Based Reasoning:**
- ontological information as part of data
- logic for meta-reasoning on top
- same data can be viewed under different semantics
Ontologies for Wikidata?
A Simple Example

Wikidata declares the `spouse` property to be symmetric:

![Diagram showing the spouse relationship between Taylor and Burton with start and end times.]

An axiom of symmetry:

$$\forall x, y, z_1, z_2, v. \text{spouse}_{\text{in}}(x, v) \land \text{spouse}_{\text{out}}(v, y) \land \text{start}(v, z_1) \land \text{end}(v, z_2) \rightarrow \exists w. \text{spouse}_{\text{in}}(y, w) \land \text{spouse}_{\text{out}}(w, x) \land \text{start}(w, z_1) \land \text{end}(w, z_2)$$
A Simple Example

Wikidata declares the *spouse* property to be symmetric:

ABox:

\[
\text{spouse}_{\text{in}}(\text{taylor}, s) \quad \text{spouse}_{\text{out}}(s, \text{burton}) \\
\text{start}(s, 1975-10-10) \quad \text{end}(s, 1976-07-29)
\]
A Simple Example

Wikidata declares the `spouse` property to be symmetric:

```
Taylor spouse_in Taylor
  start time 1975-10-10

Burton spouse_out Burton
  end time   1976-07-29

⇒

Taylor spouse_out Taylor
  start time 1975-10-10

Burton spouse_in Burton
  end time   1976-07-29
```

**ABox:**

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Existential rules

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but it might be weakly acyclic/frontier guarded (depends on other axioms)
**Observation**: Normalisation may destroy syntactic properties

[K & Thost; ISWC 2016]

- **Acyclicity** properties are mostly often preserved
- **Linearity** and **guardedness** are lost (syntactically)
- Can sometimes recover by **denormalising** rules
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- Can sometimes recover by denormalising rules

Existential rules are a first step, but:

- Normalised rules are hard to read and write
- Not expressive enough, e.g., cannot copy arbitrary annotation sets
- Loss of structure by flattening annotations, e.g., cannot have closed-world negation on annotation sets
Annotated Logics
MARS

Idea: Change from relational structures to “relational structures with annotated tuples” [Marx, K, Thost, IJCAI 2017]
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**Idea:** Change from relational structures to “relational structures with annotated tuples” [Marx, K, Thost, IJCAI 2017]

**Multi-Attributed Relational Structures (MARS):**

- standard interpretation domain $\Delta^I$
- finite annotation sets $S \in \mathcal{P}_{\text{fin}}(\Delta^I \times \Delta^I)$
- $n$-ary relations $r$ interpreted as $r^I \subseteq (\Delta^I)^n \times \mathcal{P}_{\text{fin}}(\Delta^I \times \Delta^I)$
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Multi-Attributed Predicate Logic (MAPL)
- Ground fact:
  $\text{spouse}(\text{taylor}, \text{burton})@\{\text{start} : 1975, \text{end} : 1976\}$
- Object and set variables:
  $\forall x, y, Z. \text{spouse}(x, y)@Z \rightarrow \text{spouse}(y, x)@Z$
Theorem: MAPL is equivalent to Weak Second-Order Logic, hence reasoning is not semi-decidable.
Expressivity of MAPL

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**Research goal:** Identify practical fragments
Expressivity of MAPL

Theorem: MAPL is equivalent to Weak Second-Order Logic, hence reasoning is not semi-decidable.

Research goal: Identify practical fragments

A decidable fragment:

MAPL Rules (MARPL)

- Horn rules, with all variables universally quantified
- all set variables bound in body atoms

Example: $\forall x, y, Z.\text{spouse}(x, y)@Z \rightarrow \text{spouse}(y, x)@Z$
MARPL: Additional Features

We really need more expressive features

Conditions on annotation sets

- \( Z \): 
  \[
  \text{start: } 1975, \text{end: } \ast
  \]
  \( Z \):
  "\( Z \) has given start and some end, but nothing more"

- \( \lfloor \text{start: } 1975 \rfloor (Z) \):
  "\( Z \) has given start, and possibly more"

Inferring new annotation sets

- Support declarative definition of deterministic functions that derive new sets
- Example: 
  \( \text{employer}(x, \text{cern}) \land \lfloor \text{pos: } \text{fellow} \rfloor (Z) \rightarrow \text{cernFellow}(x) \)
  \( \text{start: } Z, \text{end: } Z \)

{ supported in MARPL rule heads

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  \]

$\leadsto$ supported in MARPL rule heads
Theorem: Conjunctive query answering over MARPL ontologies is ExpTime-complete, both for combined complexity and for data complexity.
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Problem?
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Problem?

- **Not really**: hardness requires annotation sets of unbounded size (not a practical concern)
- **Actually, it’s a feature**: high data complexity enables powerful meta-reasoning in query-based approaches
MARPL is a simple rule language
(“Datalog for annotated logic”)

How about DLs?
Attributed Description Logics

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(“Datalog for annotated logic”)

How about DLs?

Attributed Description Logics
see DL talk later today [K et al., ISWC 2017]
Attributed Description Logics

MARPL is a simple rule language ("Datalog for annotated logic")

How about DLs?

Attributed Description Logics
see DL talk later today [K et al., ISWC 2017]

How about attributed existential rules?

∼ future work
The Future of KR
Problem solved?

So all we need to marry KG and KR are attributed logics?
Problem solved?

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Surely not – many other areas need more work!
Problem solved?

So all we need to marry KG and KR are attributed logics?

Surely not – many other areas need more work!

We also need to change some of our premises:

<table>
<thead>
<tr>
<th>Traditional KR View</th>
<th>vs.</th>
<th>Knowledge Graphs View</th>
</tr>
</thead>
<tbody>
<tr>
<td>schema first</td>
<td></td>
<td>data first</td>
</tr>
<tr>
<td>unique purpose</td>
<td></td>
<td>multi-purpose</td>
</tr>
<tr>
<td>fixed application</td>
<td></td>
<td>emerging applications</td>
</tr>
<tr>
<td>closed expert team</td>
<td></td>
<td>open community/many teams</td>
</tr>
</tbody>
</table>
Still Looking for the “Unifying Logic”?

- User Interface & Applications
- Trust
- Proof
- Unifying Logic
- Query: SPARQL
- Ontology: OWL
- Rule: RIF
- RDFS
- Data interchange: RDF
- XML
- URI/IRI

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Ontologies for Knowledge Graphs?

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Conclusions

Summary

- Knowledge Graphs are enriched graphs
- Wikidata: large ABox / “ontology” / path queries
- Query-based reasoning: plug’n’play semantics for data
- Existential rules & DLs: struggling with annotations
- Attributed logics: MAPL & MARPL (& attributed DLs)

What next?

View KR as a declarative computing paradigm & start facing the competition in this space!

Revisit “Computing in Logic” (but don’t go back to Prolog!)


