TECHNISCHE
UNIVERSITÄT
DRESDEN

ONTOLOGIES FOR KNOWLEDGE GRAPHS?

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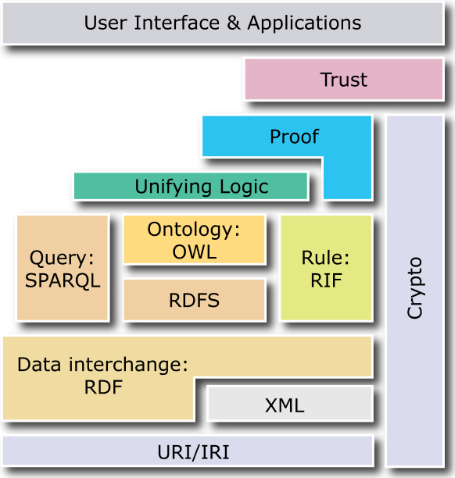
reporting on joint work with Stefan Bischoff, Fredo Erxleben, Michael Günther, Maximilian Marx[†], Julian Mendez, Ana Ozaki[†], Axel Polleres, Sebastian Rudolph, Veronika Thost[†], and Denny Vrandečić

[†] Knowledge-Based Systems

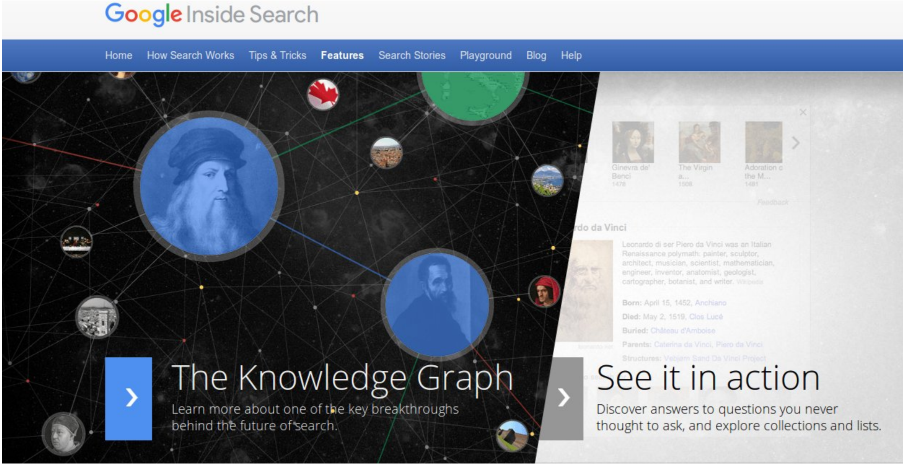
TU Dresden

DL Workshop 2017

The Semantic Web (2007)



2012: The Knowledge Graph



Ginevra de' Benci 1478

The Virgin a... 1508

Adoration o the M... 1481

rdo da Vinci

Leonardo di ser Piero da Vinci was an Italian Renaissance polymath: painter, sculptor, architect, musician, scientist, mathematician, engineer, inventor, anatomist, geologist, cartographer, botanist, and writer. Wikipedia

Born: April 15, 1452, Anchiano

Died: May 2, 1519, Clos Lucé

Buried: Château d'Amboise

Parents: Caterina da Vinci, Piero da Vinci

Structures: Vebjørn Sand Da Vinci Project

The Knowledge Graph

Learn more about one of the key breakthroughs behind the future of search.

See it in action

Discover answers to questions you never thought to ask, and explore collections and lists.

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

More Knowledge Graphs

What is a Knowledge Graph?

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

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Charateristics 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

What is a Knowledge Graph?

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Charateristics 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

Summary

Knowledge graphs

- introduce graph-based data models
- requiring declarative analytics
- that make non-local connections

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reasoning on graphs

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Conclusion

Symbolic KR is the key technology
in modern data management

especially in AI applications

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} reasoning on graphs

Conclusion

Symbolic KR is th y technology
in mode nagement

especia y in AI applications

Not really happening

WIKIDATA

A Free Knowledge Graph

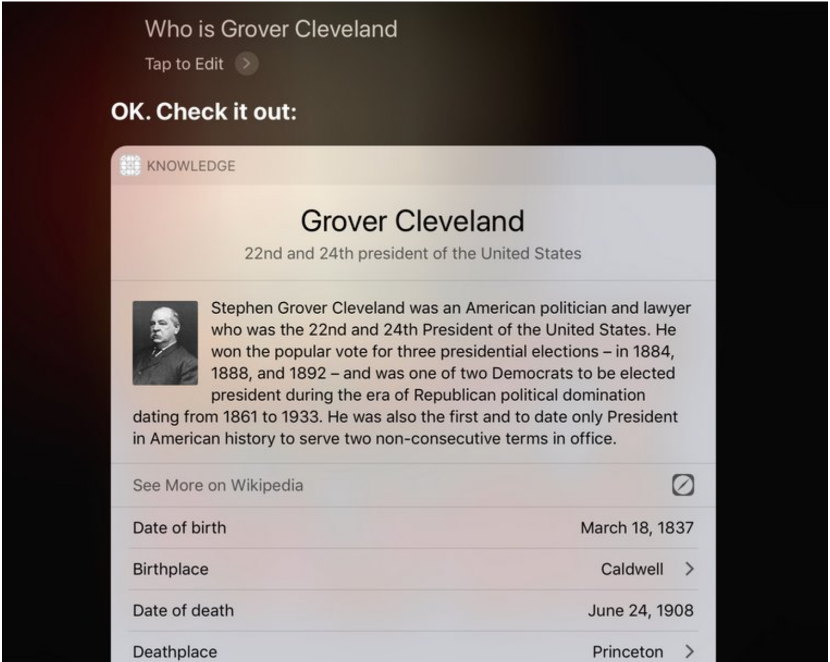
Wikidata

- 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

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.

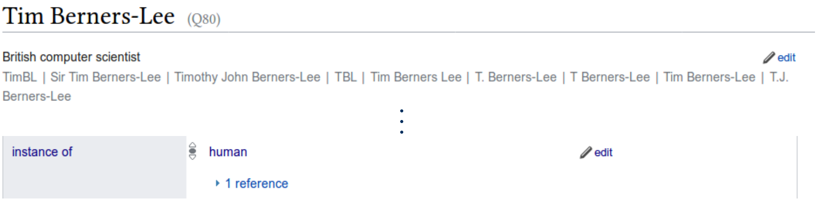
Date of birth	March 18, 1837
Birthplace	Caldwell >
Date of death	June 24, 1908
Deathplace	Princeton >

Tim Berners-Lee (Q80)

British computer scientist

edit

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



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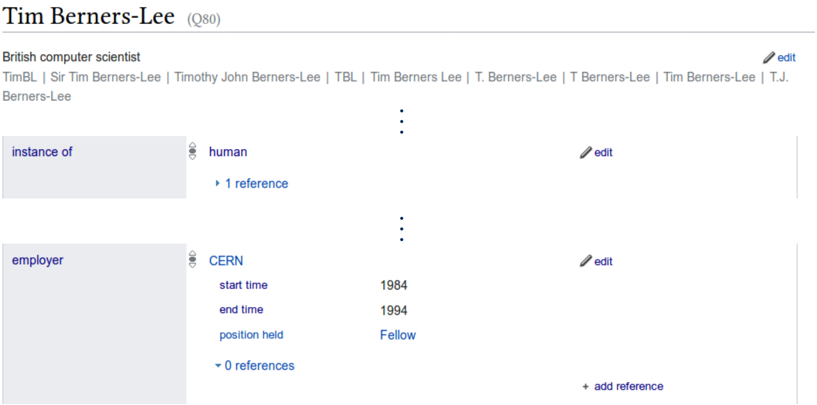
⋮

instance of	human 1 reference



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instance of	human ▸ 1 reference

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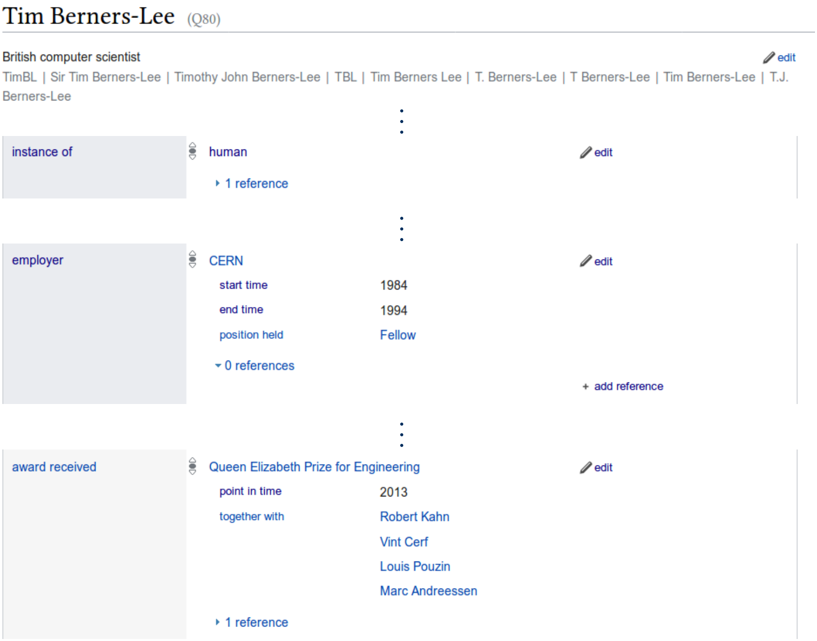
employer	CERN	
	start time	1984
	end time	1994
	position held	Fellow
	▾ 0 references	



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instance of — human

▸ 1 reference

⋮

employer — CERN

start time 1984

end time 1994

position held Fellow

▾ 0 references

⋮

award received — Queen Elizabeth Prize for Engineering

point in time 2013

together with Robert Kahn

Vint Cerf

Louis Pouzin

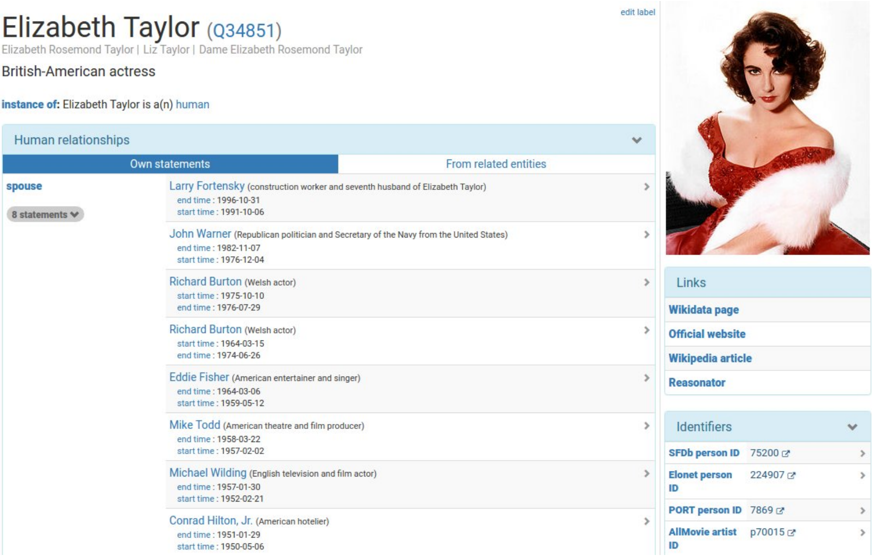
Marc Andreessen

▸ 1 reference

Statements in Wikidata

Wikidata's basic information units

- Built from Wikidata items ("CERN", "Vint Cerf"), Wikidata properties ("award received", "end time"), and data values ("2013")
- Based on directed edges ("Tim Berners-Lee –employer→ CERN")
- Annotated with property-value pairs ("end time: 1994")
  - same property can have multiple annotation values ("together with: Robert Kahn, Vint Cerf, . . . ")
  - same properties/values used in directed edges and annotations
- Items and properties can be subjects/values in statements
- Multi-graph



edit label

Elizabeth Taylor (Q34851)

Elizabeth Rosemond Taylor | Liz Taylor | Dame Elizabeth Rosemond Taylor

British-American actress

instance of: Elizabeth Taylor is a(n) human

Human relationships

Own statements | From related entities

spouse

8 statements

- Larry Fortensky (construction worker and seventh husband of Elizabeth Taylor)
  - end time : 1996-10-31
  - start time : 1991-10-06
- John Warner (Republican politician and Secretary of the Navy from the United States)
  - end time : 1982-11-07
  - start time : 1976-12-04
- Richard Burton (Welsh actor)
  - start time : 1975-10-10
  - end time : 1976-07-29
- Richard Burton (Welsh actor)
  - start time : 1964-03-15
  - end time : 1974-06-26
- Eddie Fisher (American entertainer and singer)
  - end time : 1964-03-06
  - start time : 1959-05-12
- Mike Todd (American theatre and film producer)
  - end time : 1958-03-22
  - start time : 1957-02-02
- Michael Wilding (English television and film actor)
  - end time : 1957-01-30
  - start time : 1952-02-21
- Conrad Hilton, Jr. (American hotelier)
  - end time : 1951-01-29
  - start time : 1950-05-06

Links

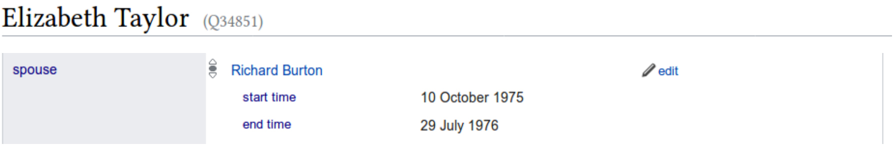
- **Wikidata page**
- **Official website**
- **Wikipedia article**
- **Reasonator**

Identifiers

SFDb person ID	75200
Elonet person ID	224907
PORT person ID	7869
AllMovie artist ID	p70015

Fig.: Taylor standing in multiple relations; from `https://tools.wmflabs.org/sqid/#/view?id=Q34851`

Wikidata Statements in Terms of Graphs



Elizabeth Taylor (Q34851)

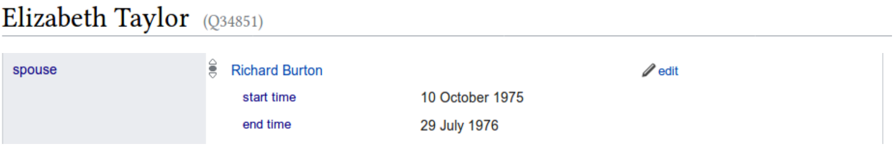
spouse

Richard Burton

start time 10 October 1975

end time 29 July 1976

Wikidata Statements in Terms of Graphs



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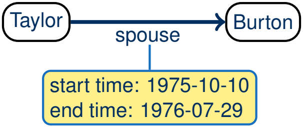
“Property Graph”:



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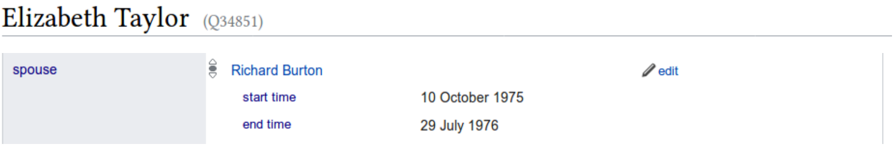

Elizabeth Taylor (Q34851)

spouse	Richard Burton	edit
	start time	10 October 1975
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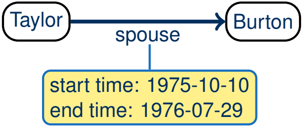


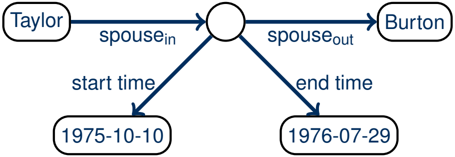
Taylor

spouse

Burton

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

“RDF”:



Taylor

$\text{spouse}_{\text{in}}$

$\text{spouse}_{\text{out}}$

Burton

start time

end time

1975-10-10

1976-07-29

Ontological Modelling in Wikidata

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)

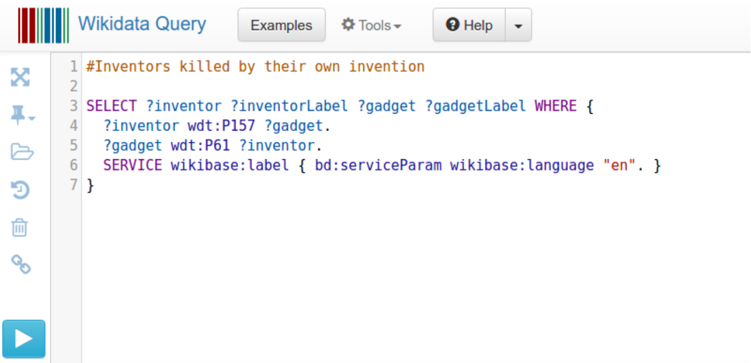
Property characteristics/constraints

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

Queries on Wikidata

SPARQL query service: `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 {
  ?inventor wdt:P157 ?gadget.
  ?gadget wdt:P61 ?inventor.
  SERVICE wikibase:label { bd:serviceParam wikibase:language "en". }
}
```

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Initial analysis of the non-public logs:

- $\leq$1% queries from human traffic (400–500K per month)
- $\geq$99% service calls from tools and robots
- Irregular distributions and biases – hard to analyse

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Property paths used for transitivity reasoning

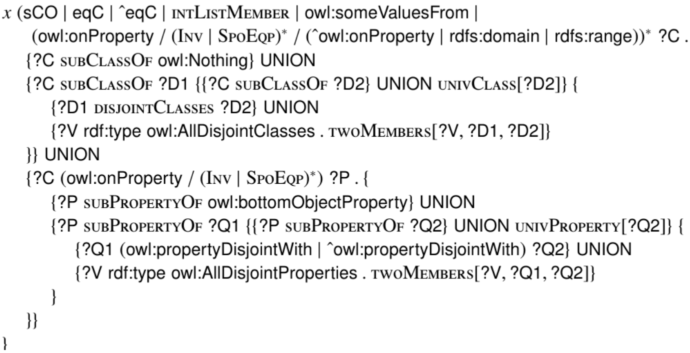
- used in about 50% of human subclass-of queries (20K)
- over 500K queries with subclass-of paths overall

(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 (sCO | eqC | ˆeqC | intListMember | owl:someValuesFrom |
   (owl:onProperty / (Inv | SpoEqp)* / (ˆowl:onProperty | rdfs:domain | rdfs:range))* ?C . {
  {?C subClassOf owl:Nothing} UNION
  {?C subClassOf ?D1 {{?C subClassOf ?D2} UNION univClass[?D2]} {
    {?D1 disjointClasses ?D2} UNION
    {?V rdf:type owl:AllDisjointClasses . twoMembers[?V, ?D1, ?D2]}
  }} UNION
  {?C (owl:onProperty / (Inv | SpoEqp)*) ?P . {
    {?P subPropertyOf owl:bottomObjectProperty} UNION
    {?P subPropertyOf ?Q1 {{?P subPropertyOf ?Q2} UNION univProperty[?Q2]} {
      {?Q1 (owl:propertyDisjointWith | ˆowl:propertyDisjointWith) ?Q2} UNION
      {?V rdf:type owl:AllDisjointProperties . twoMembers[?V, ?Q1, ?Q2]}
    }
  }}
}
```

Fig.: A query that checks if x is equivalent to $\perp$ (abbreviated)

Beyond OWL QL

SPARQL cannot support arbitrary OWL reasoning:

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- SPARQL can only perform reasoning in NL

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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]

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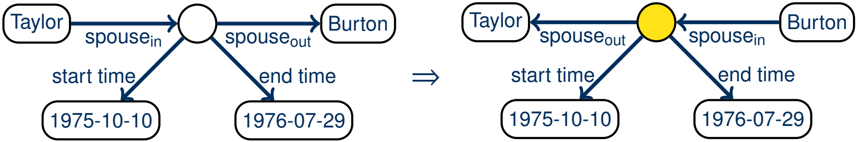
Query-Based Reasoning:

- ontologicl 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:



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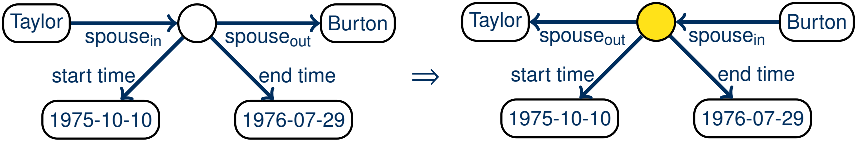

ABox:

$$\text{spouse}_{\text{in}}(\text{taylor}, s) \quad \text{spouse}_{\text{out}}(s, \text{burton})$$

$$\text{start}(s, \mathtt{1975\text{-}10\text{-}10}) \quad \text{end}(s, \mathtt{1976\text{-}07\text{-}29})$$

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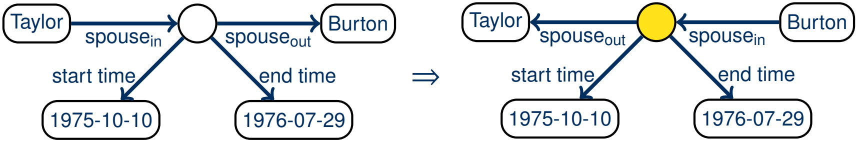

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An axiom of symmetry:

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

Existential rules

$$\mathsf{spouse}_{\mathsf{in}}(x, v) \wedge \mathsf{spouse}_{\mathsf{out}}(v, y) \wedge \mathsf{start}(v, z_1) \wedge \mathsf{end}(v, z_2)$$
$$\rightarrow \exists w.\mathsf{spouse}_{\mathsf{in}}(y, w) \wedge \mathsf{spouse}_{\mathsf{out}}(x, y) \wedge \mathsf{start}(w, z_1) \wedge \mathsf{end}(w, z_2)$$

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but it might be weakly acyclic/frontier guarded
(depends on other axioms)

Breaking the Rules

Observation: Normalisation may destroy syntactic properties [K & Thost; ISWC 2016]

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

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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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Multi-Attributed Relational Structures (MARS):

- standard interpretation domain $\Delta^{\mathcal{I}}$
- finite annotation sets $S \in \mathcal{P}_{\text{fin}}(\Delta^{\mathcal{I}} \times \Delta^{\mathcal{I}})$
- n-ary relations r interpreted as $r^{\mathcal{I}} \subseteq (\Delta^{\mathcal{I}})^n \times \mathcal{P}_{\text{fin}}(\Delta^{\mathcal{I}} \times \Delta^{\mathcal{I}})$

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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:
  $\forall x, y, Z.\text{spouse}(x, y)@Z \to \text{spouse}(y, x)@Z$

Expressivity of MAPL

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

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Research goal: Identify practical fragments

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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

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Conditions on annotation sets Z

- $[\mathsf{start} : \mathtt{1975}, \mathsf{end} : *](Z)$:
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- $\lfloor\mathsf{start} : \mathtt{1975}\rfloor(Z)$: "$Z$ has given start, and possibly more"

$\leadsto$ supported in MARPL rule bodies

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$\rightsquigarrow$ supported in MARPL rule bodies

Inferring new annotation sets

- Support declarative definition of deterministic functions that derive new sets
- Example:

$$\begin{aligned} &\mathsf{employer}(x, \mathsf{cern})@Z \land \lfloor \mathsf{pos} : \mathsf{fellow} \rfloor(Z) \\ &\quad \to \mathsf{cernFellow}(x)@[\mathsf{start} : Z.\mathsf{start}, \mathsf{end} : Z.\mathsf{end}] \end{aligned}$$

$\rightsquigarrow$ supported in MARPL rule heads

MARPL Complexity

Theorem: Conjunctive query answering ove 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

Attributed Description Logics

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

How about DLs?

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How about attributed existential rules?

$\leadsto$ future work

The Future of KR

Problem solved?

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

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Surely not – many other areas need more work!

Problem solved?

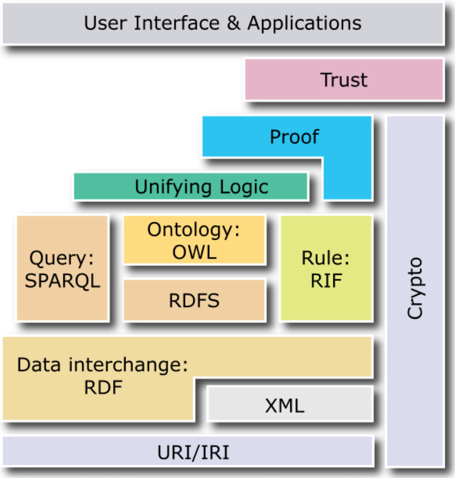
So all we need to marry KG and KR are attributed logics?

Surely not – many other areas need more work!

We also need to change some of our premises:

Traditional KR View	vs.	Knowledge Graphs View
schema first		data first
unique purpose		multi-purpose
fixed application		emerging applications
closed expert team		open community/many teams

Still Looking for the “Unifying Logic”?



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!)

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