Knowledge Representation & Reasoning: From Foundations to Products

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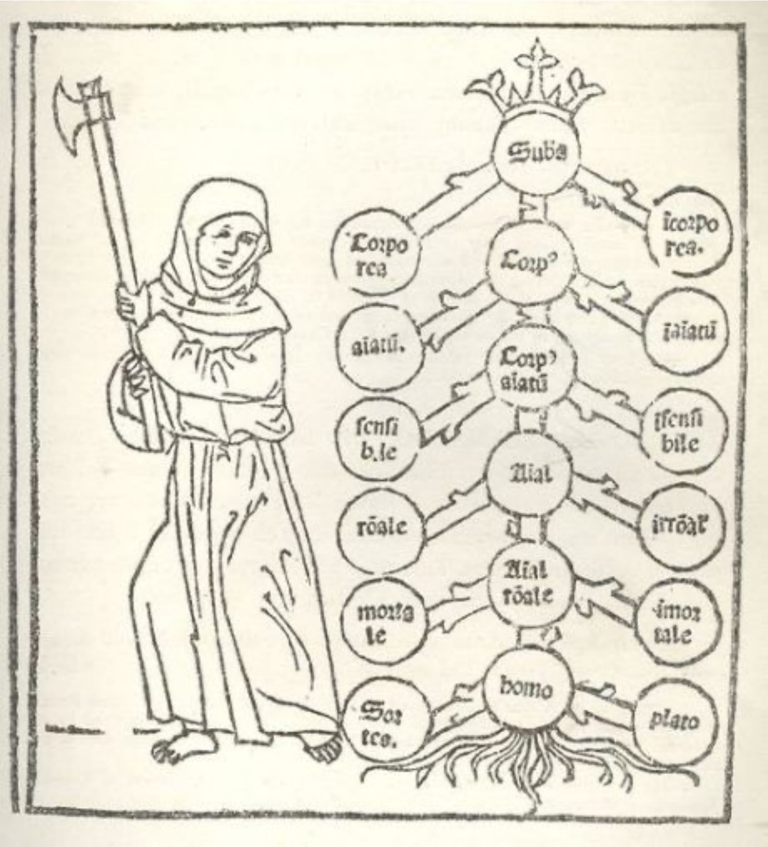
Background and Motivation

KRR Historical Perspective

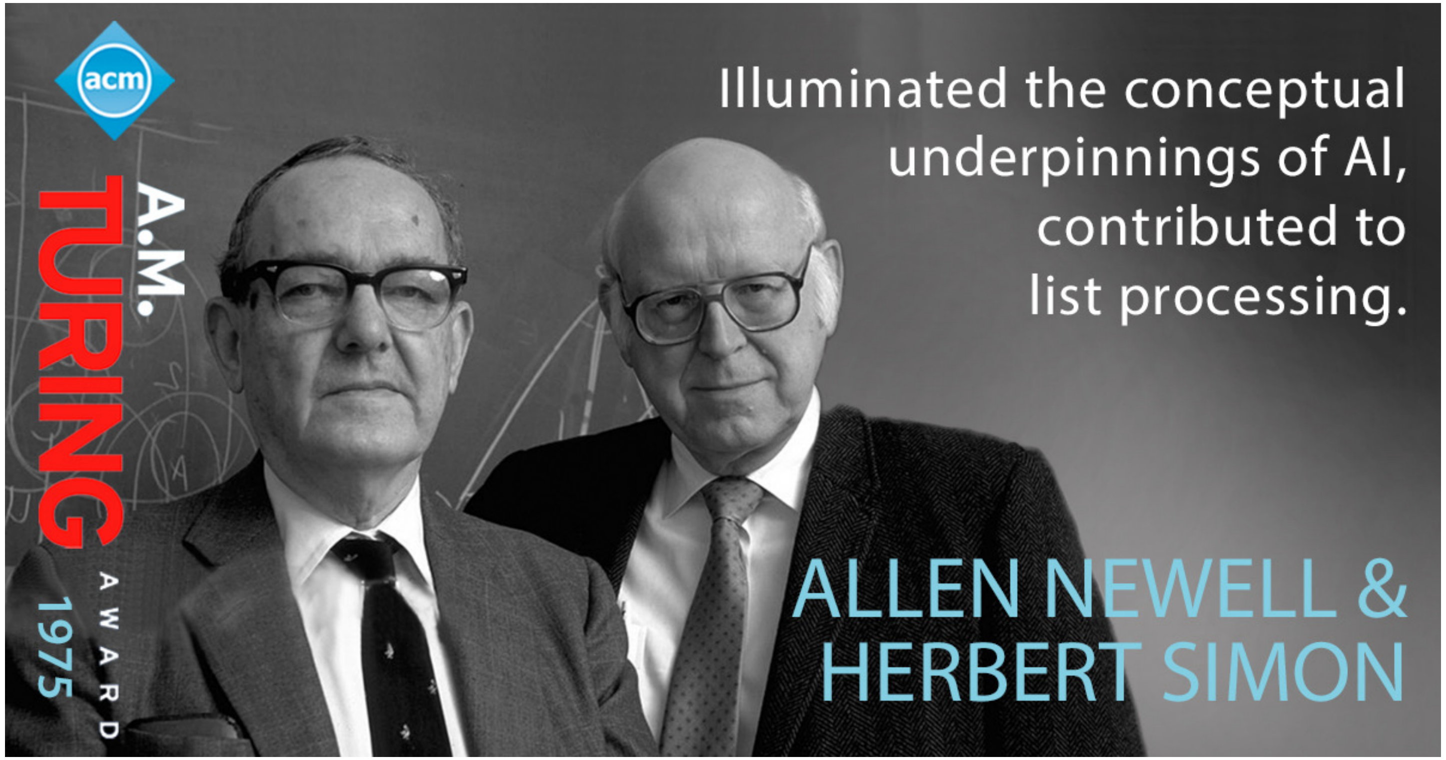
- Long and distinguished history



Porphyry’s depiction of Aristotle’s categories

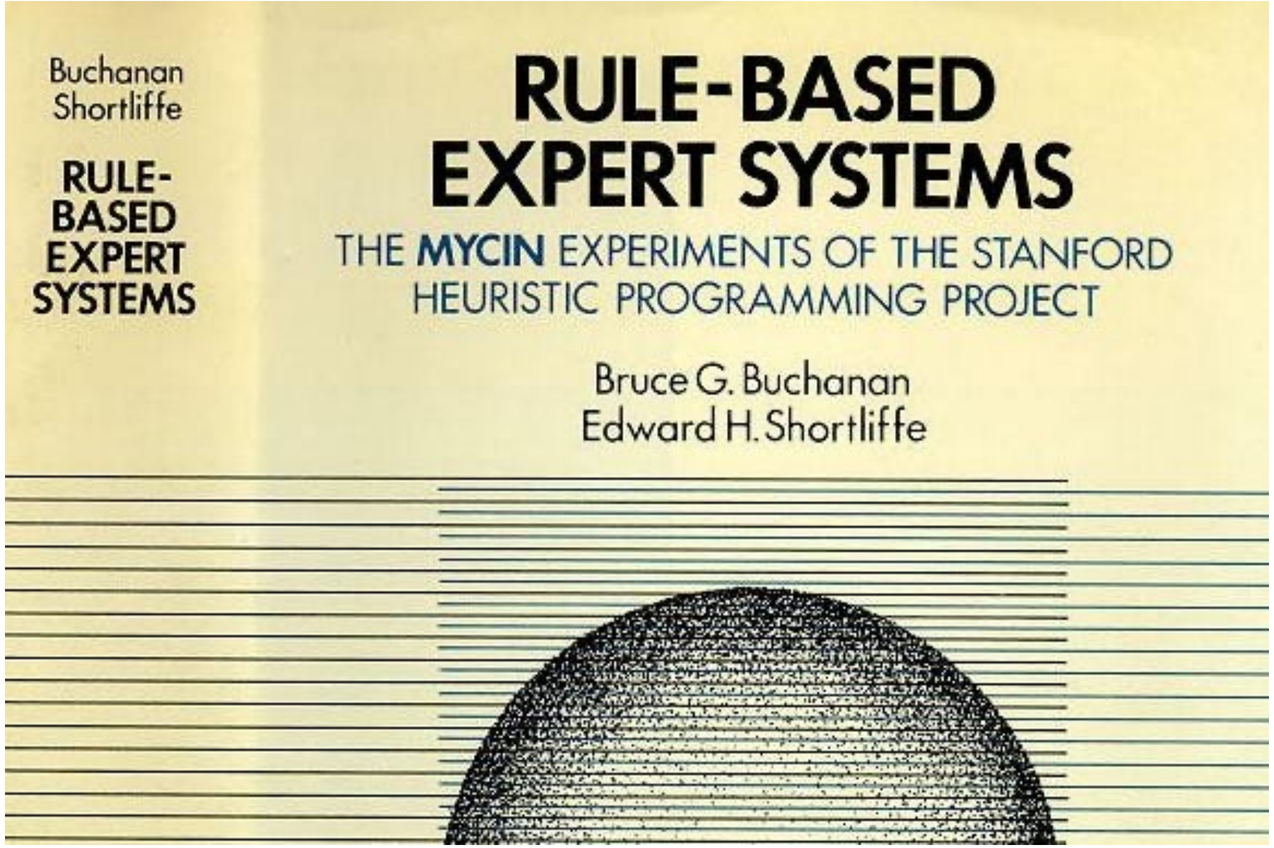
KRR Historical Perspective

- Long and distinguished history
- General Problem Solver (GPS)

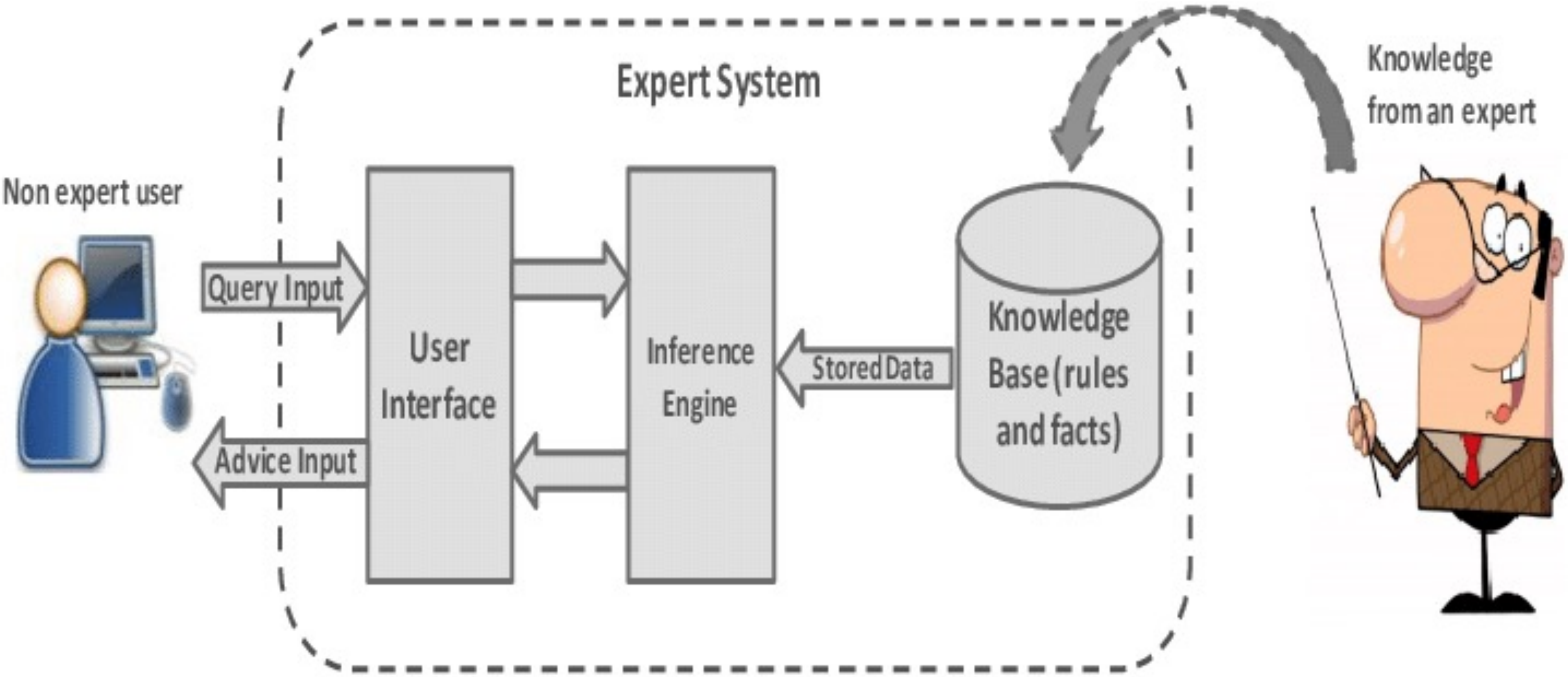


KRR Historical Perspective

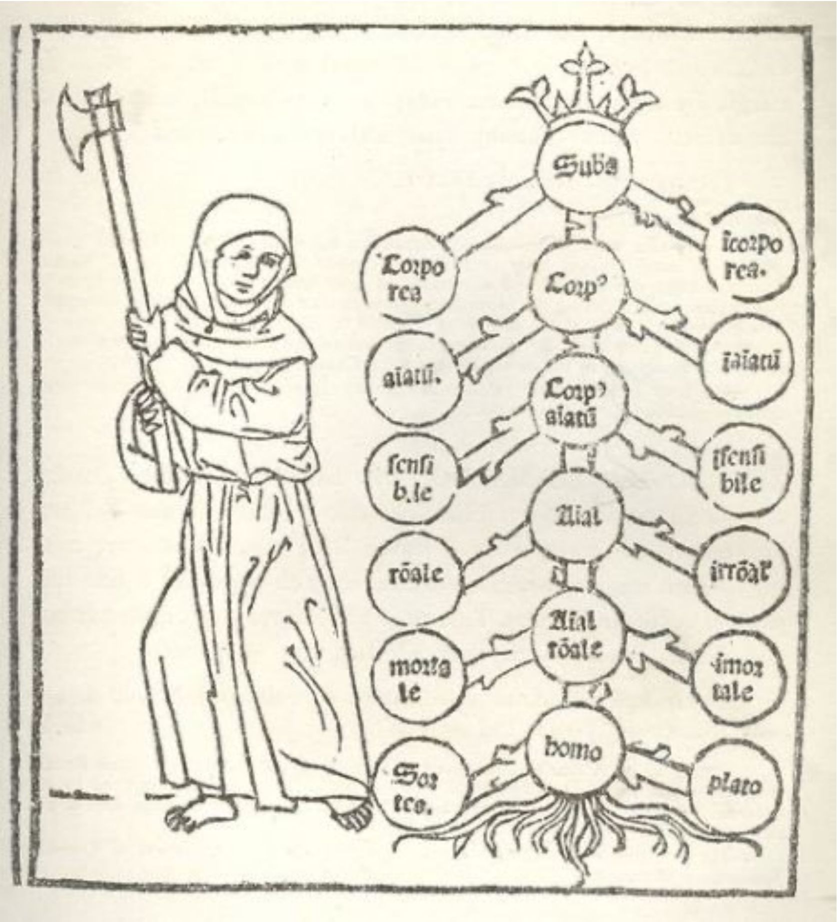
- Long and distinguished history
- General Problem Solver (GPS)
- Expert systems

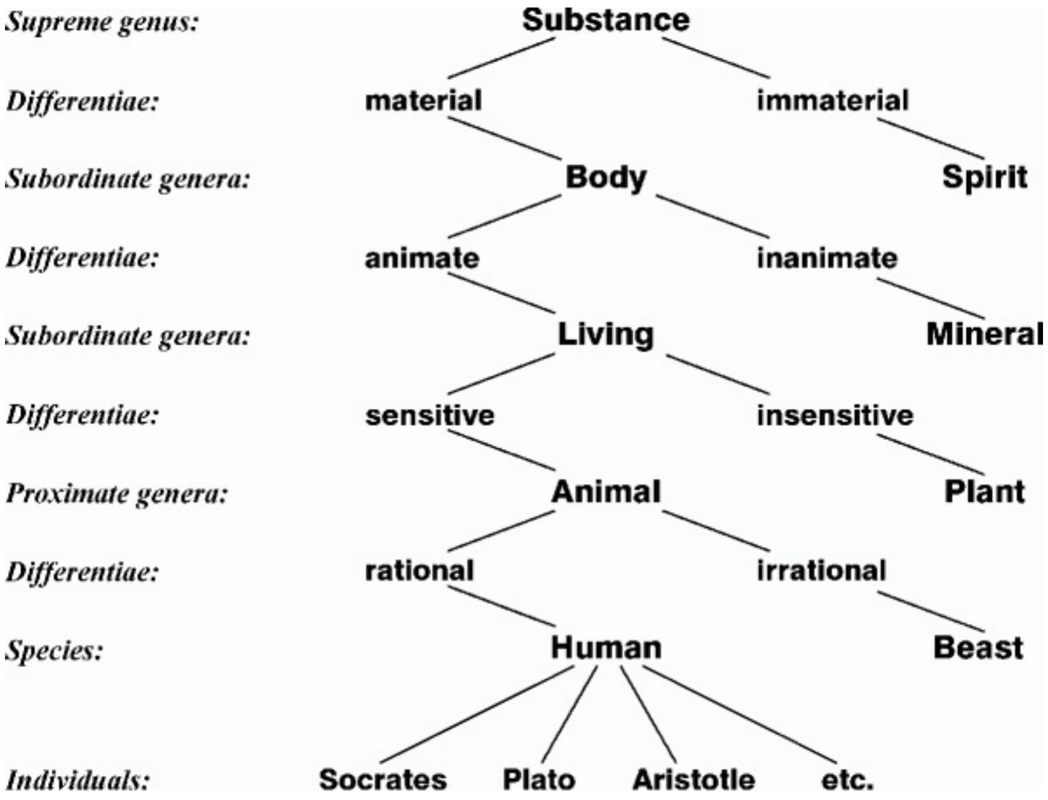


KRR Historical Perspective



Why use a graph?





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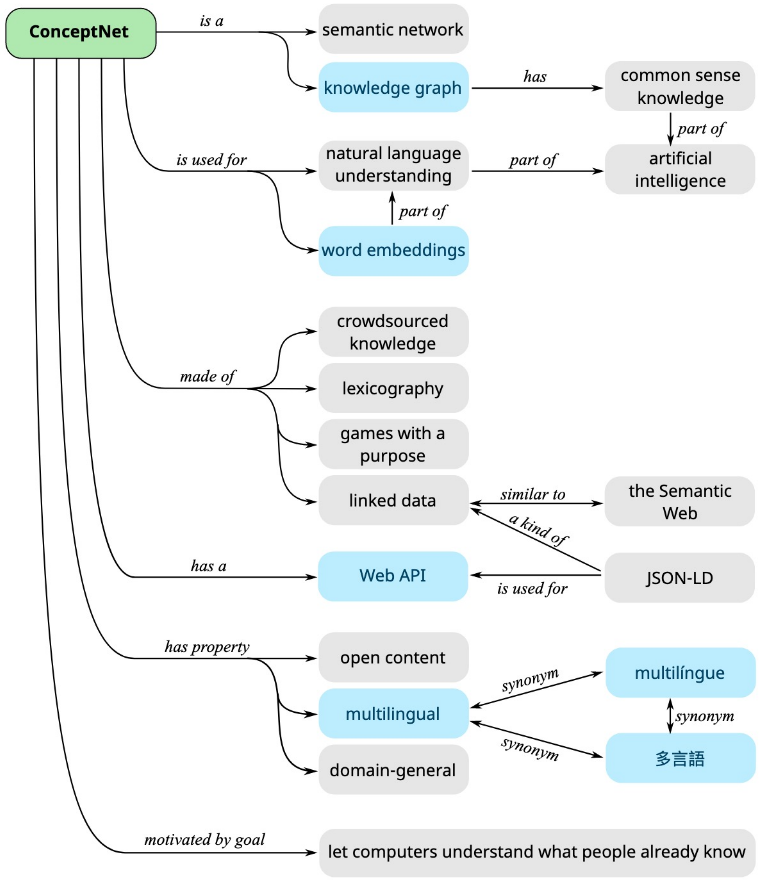

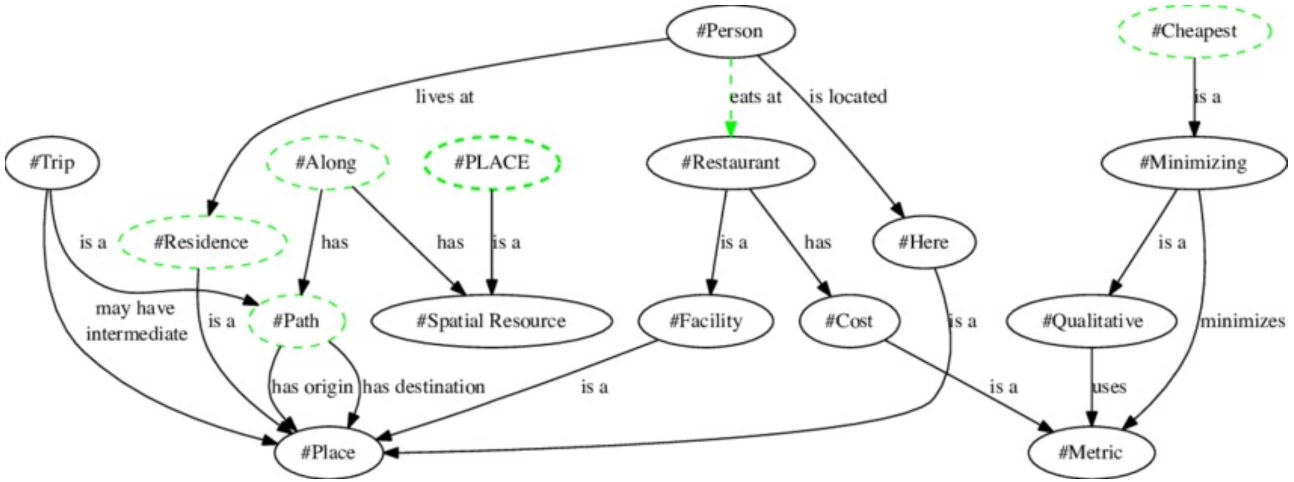

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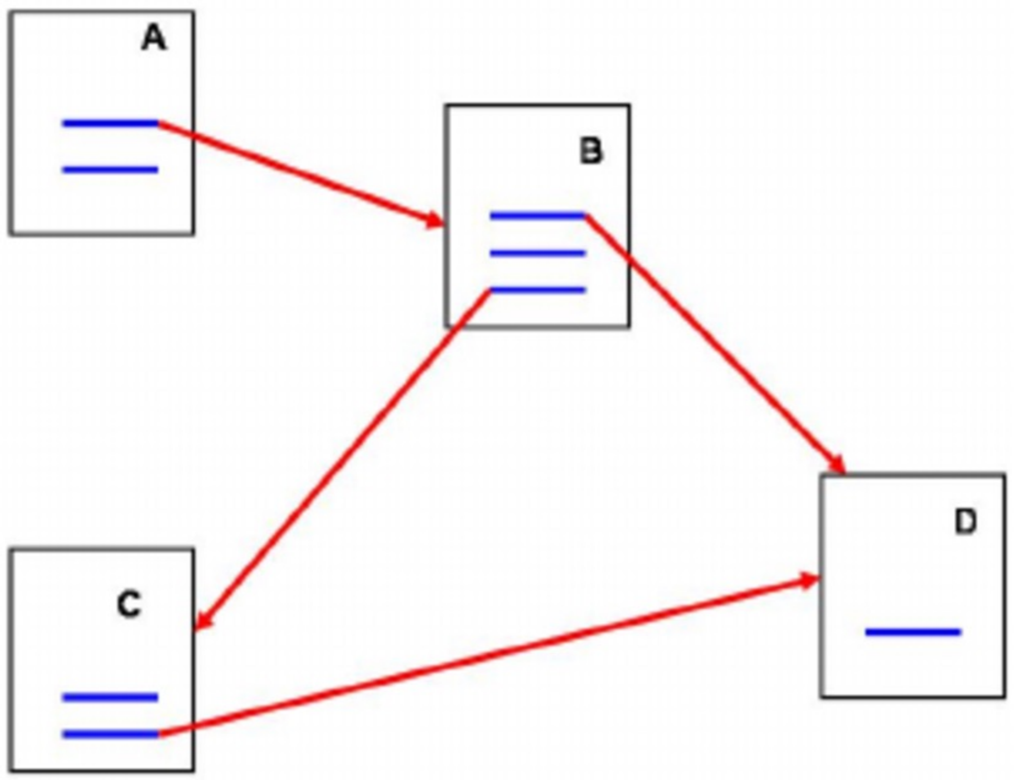

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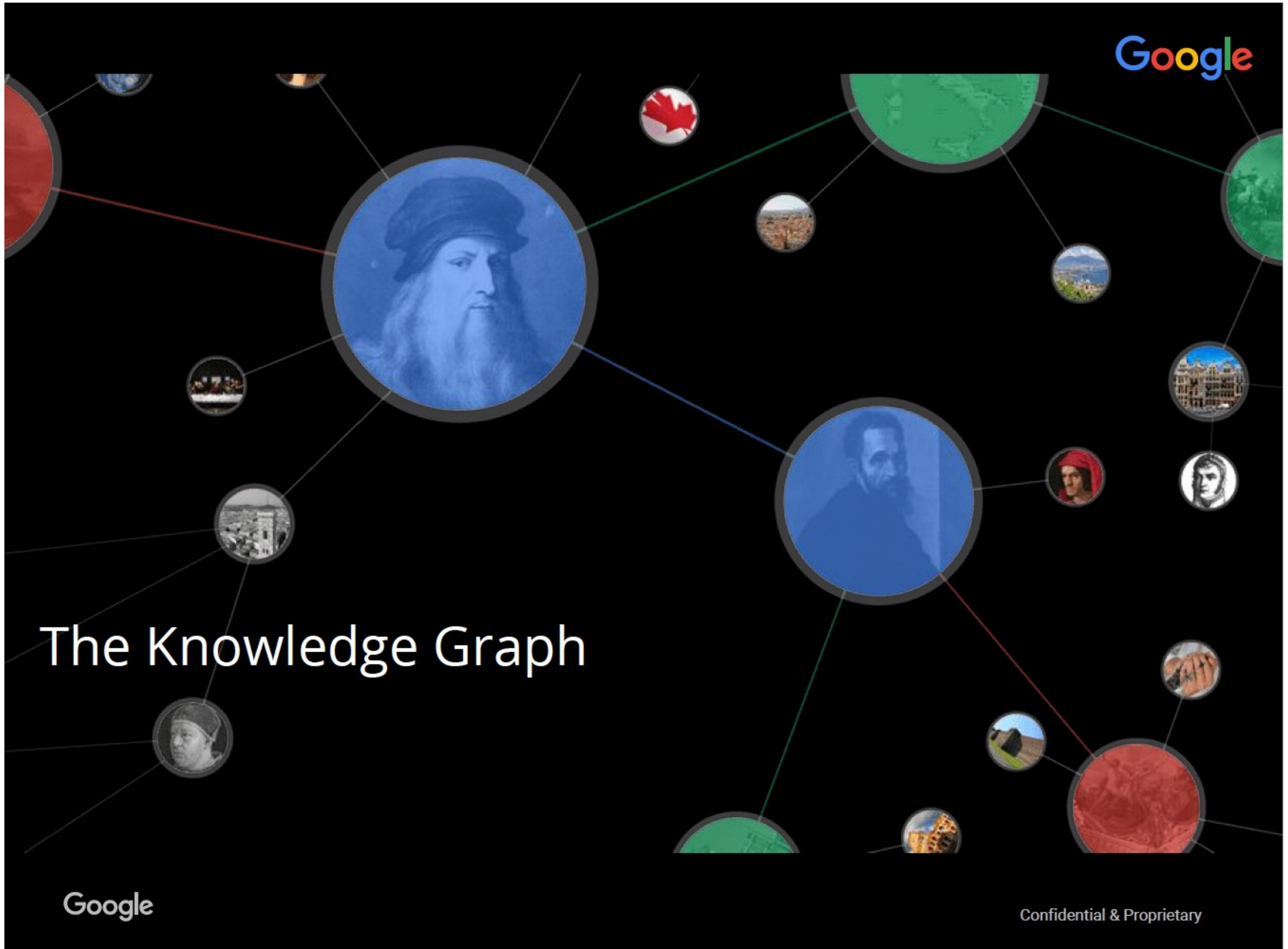


Why use a graph?

alexa

WIKIDATA

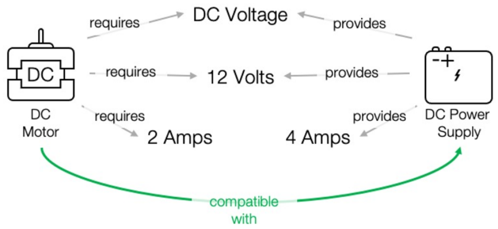
DBpedia

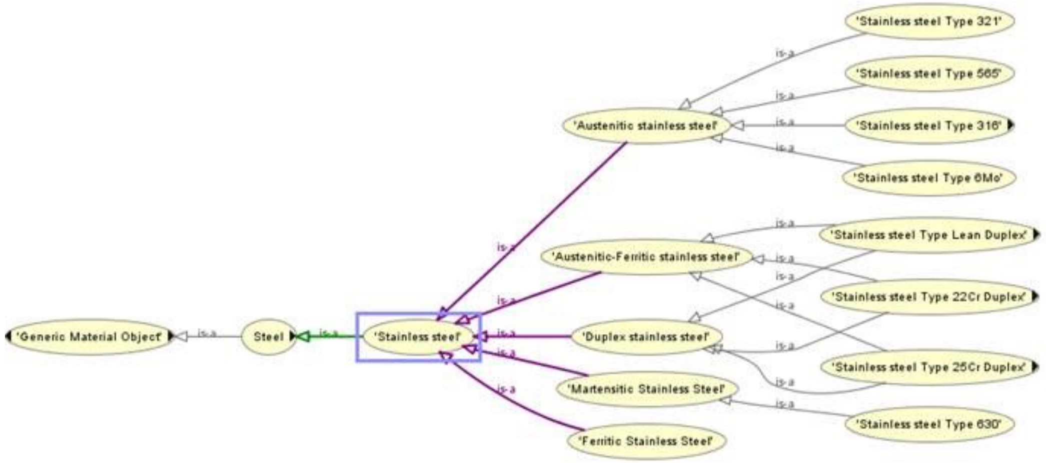
ebay Beam open source

A Distributed Knowledge Graph Store

FIBO

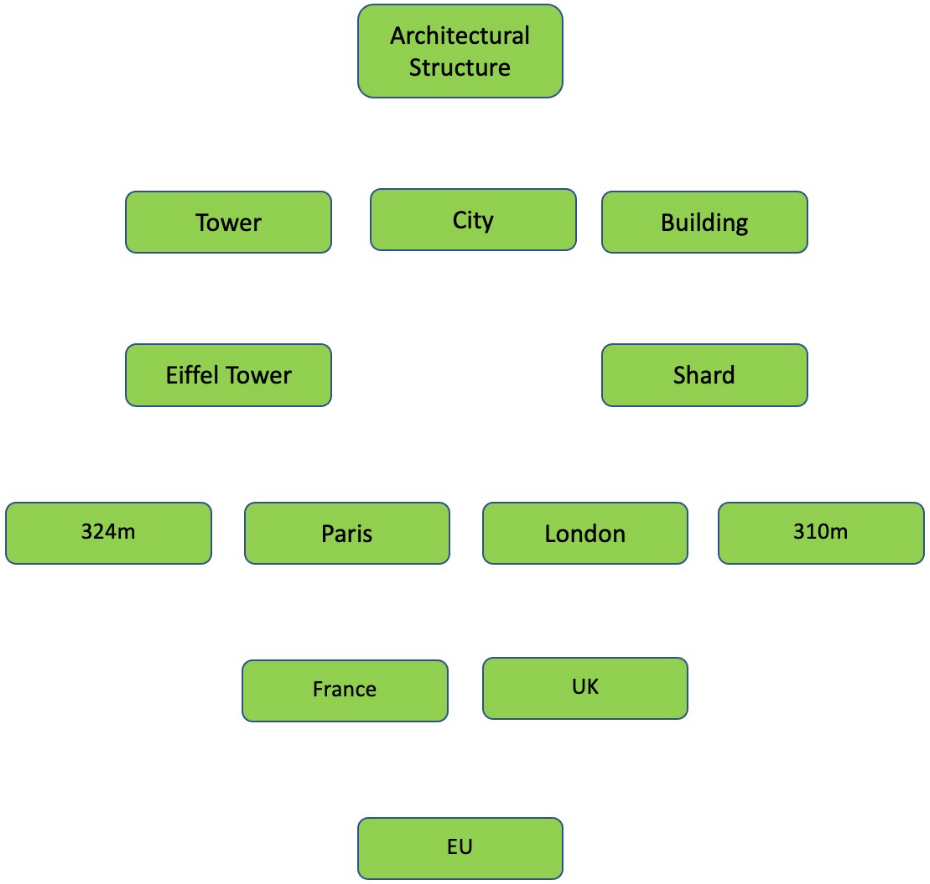
FESTO





Introduction to Knowledge Graphs

Anatomy of a Knowledge Graph



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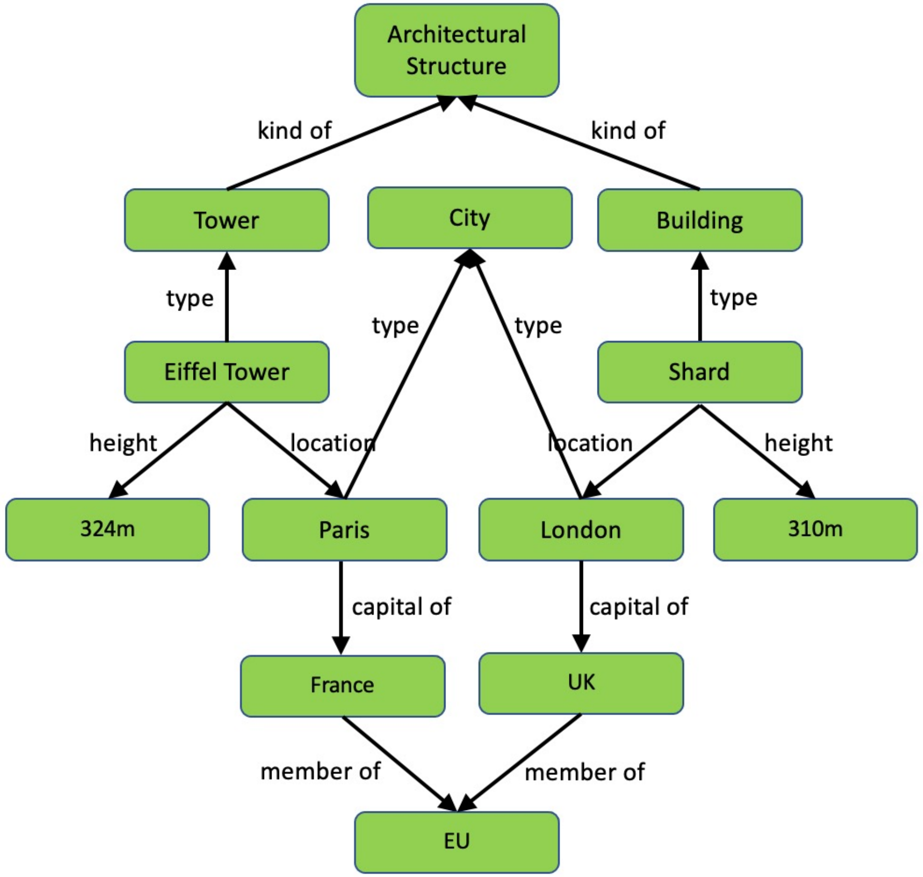

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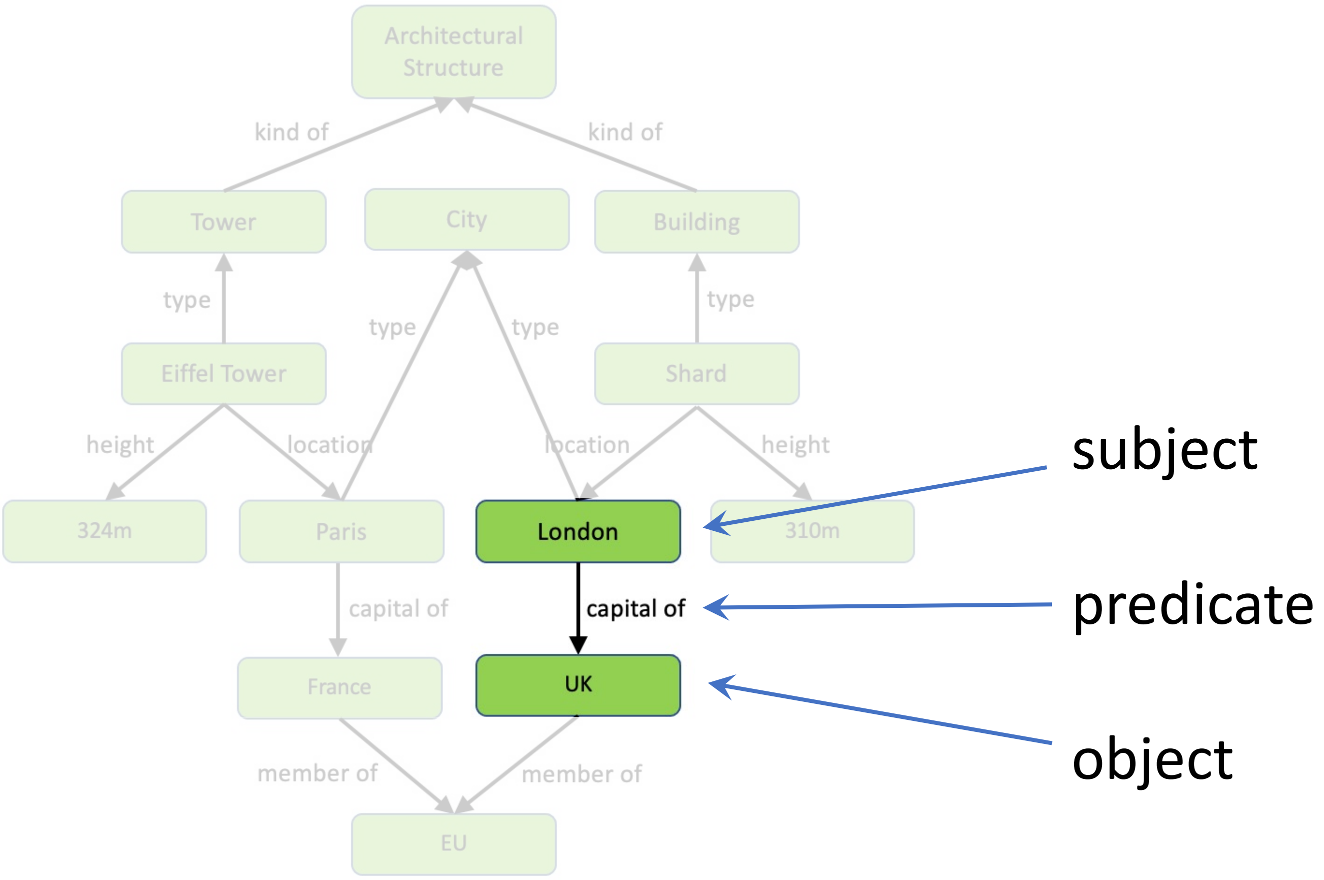

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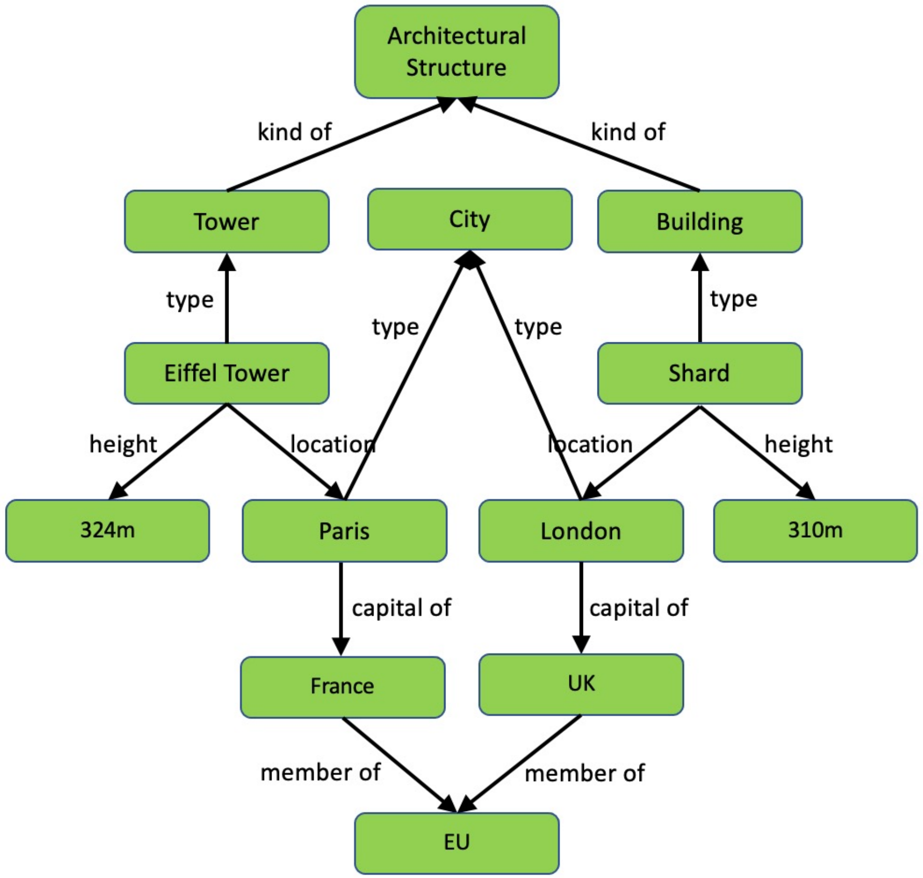

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Architectural Structure		
Name	Height	Location
Eiffel Tower	324	Paris
Shard	310	London

Tower
Name
Eiffel Tower

Building
Name
Shard

City	
Name	Capital Of
Paris	France
London	UK

Member	
Country	Union
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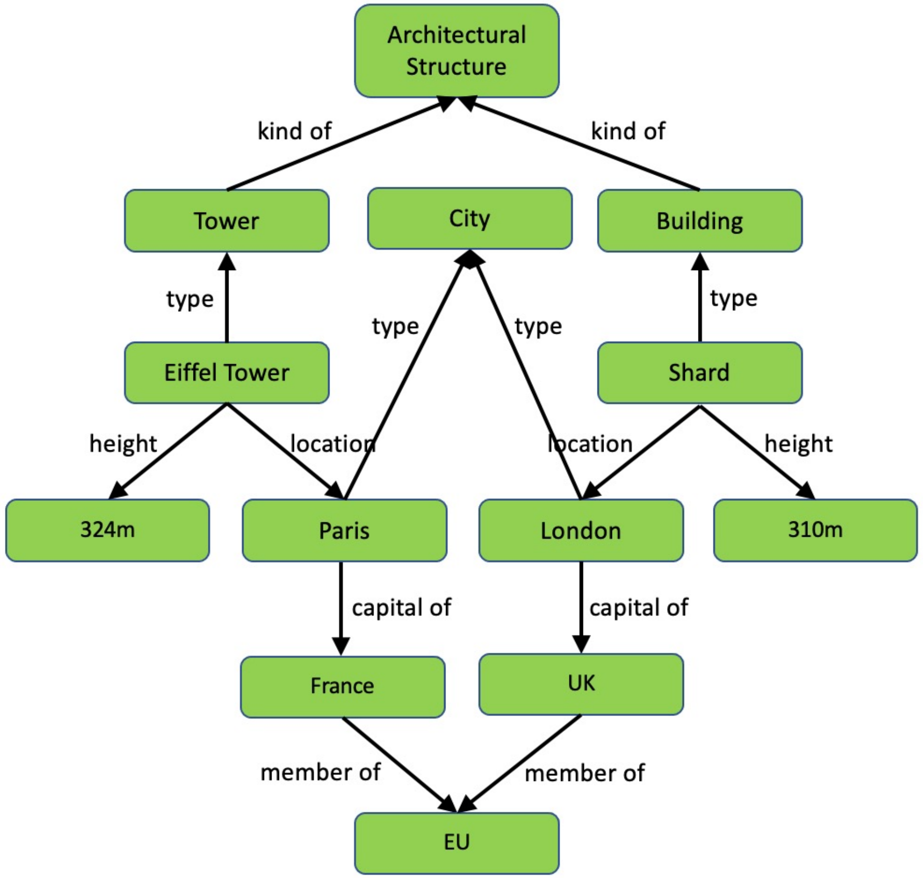

✓ Intuitive (e.g., no “foreign keys”)

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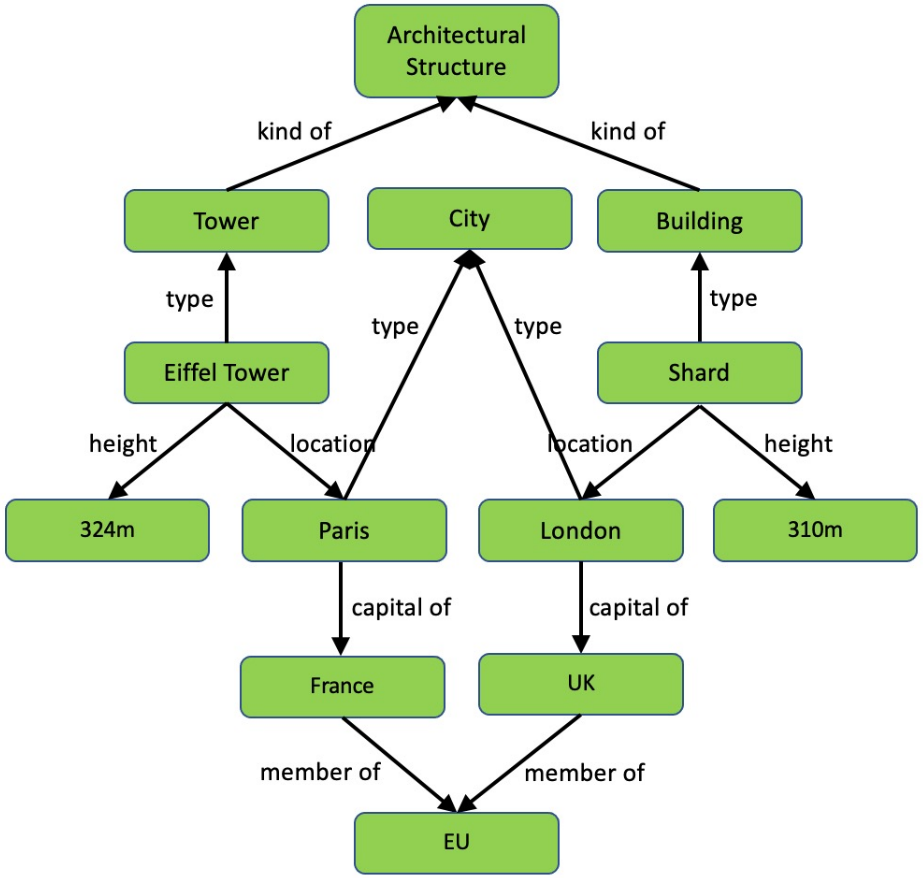

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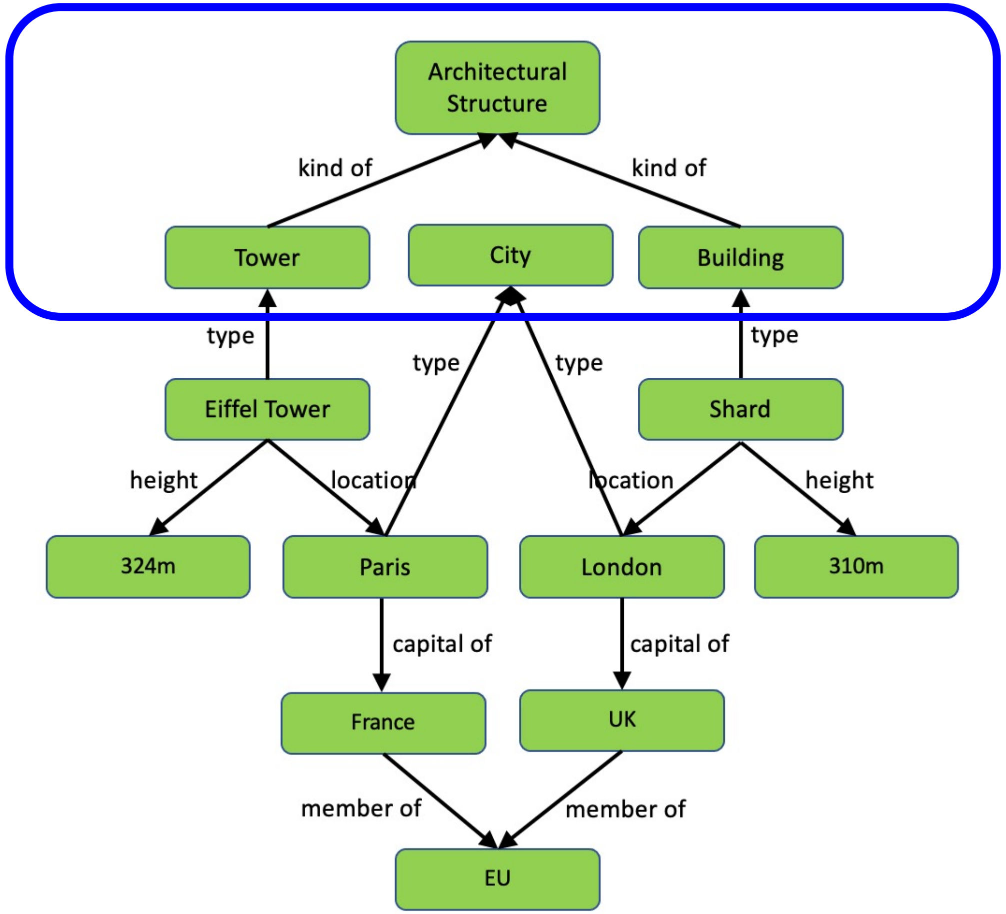

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- ✓ **Data** + **schema (ontology)**

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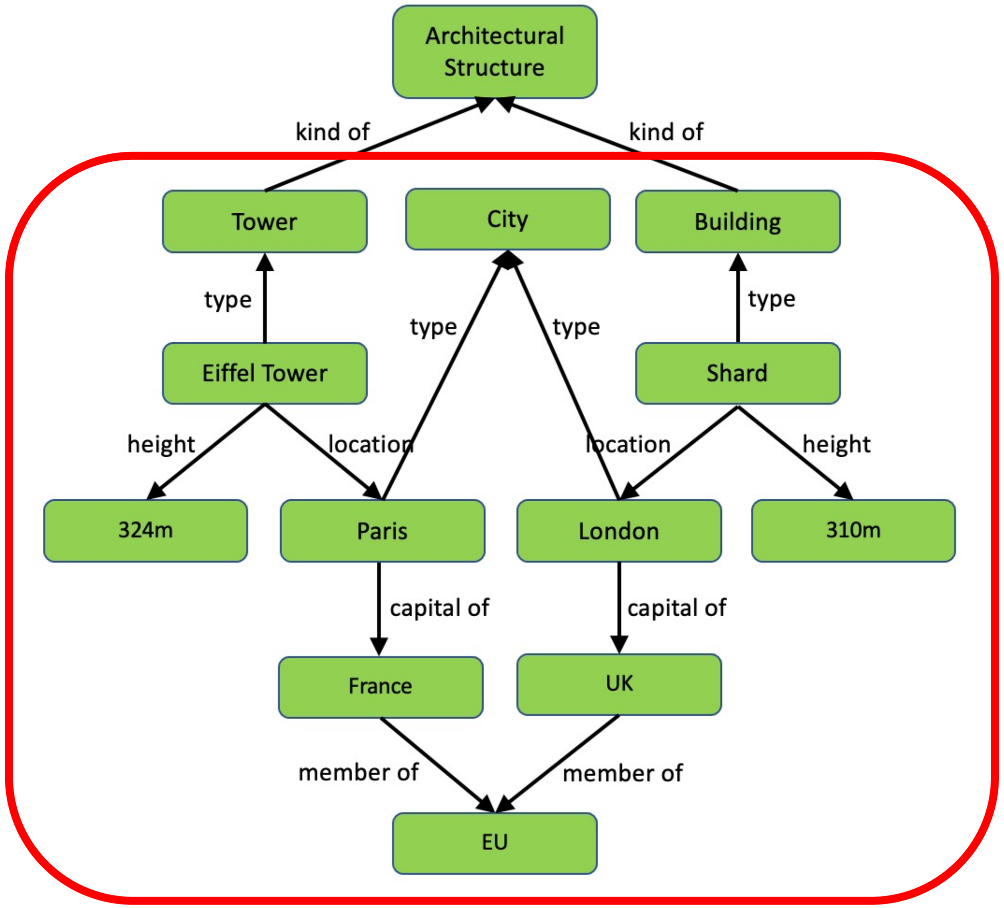

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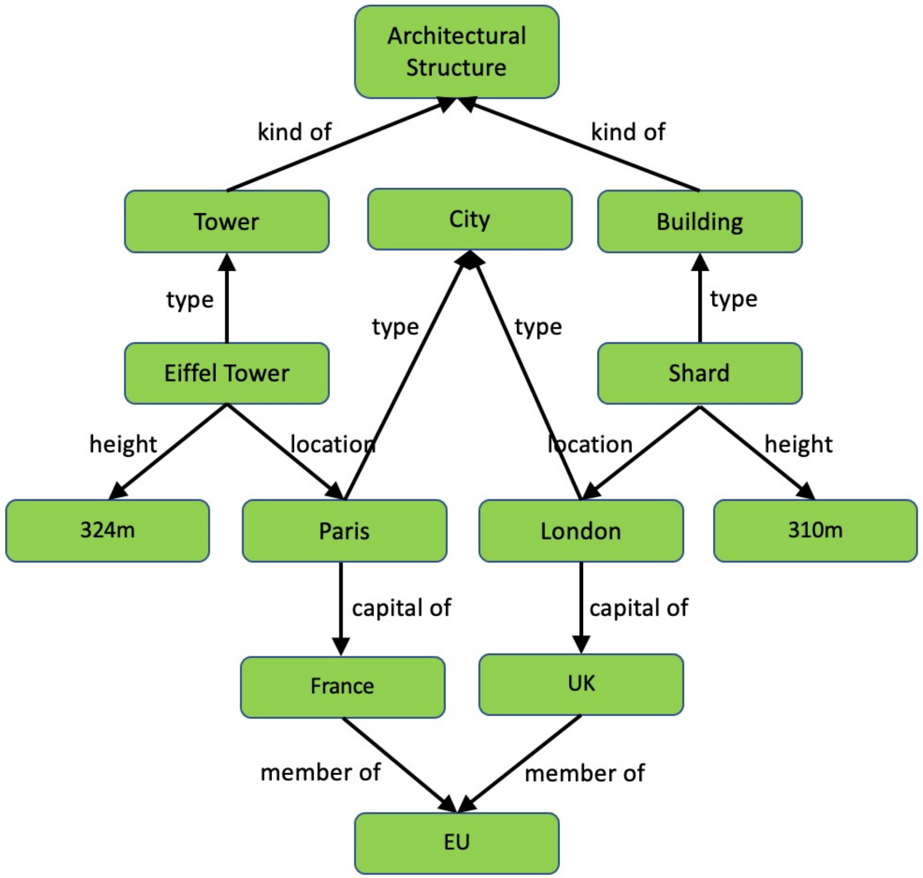

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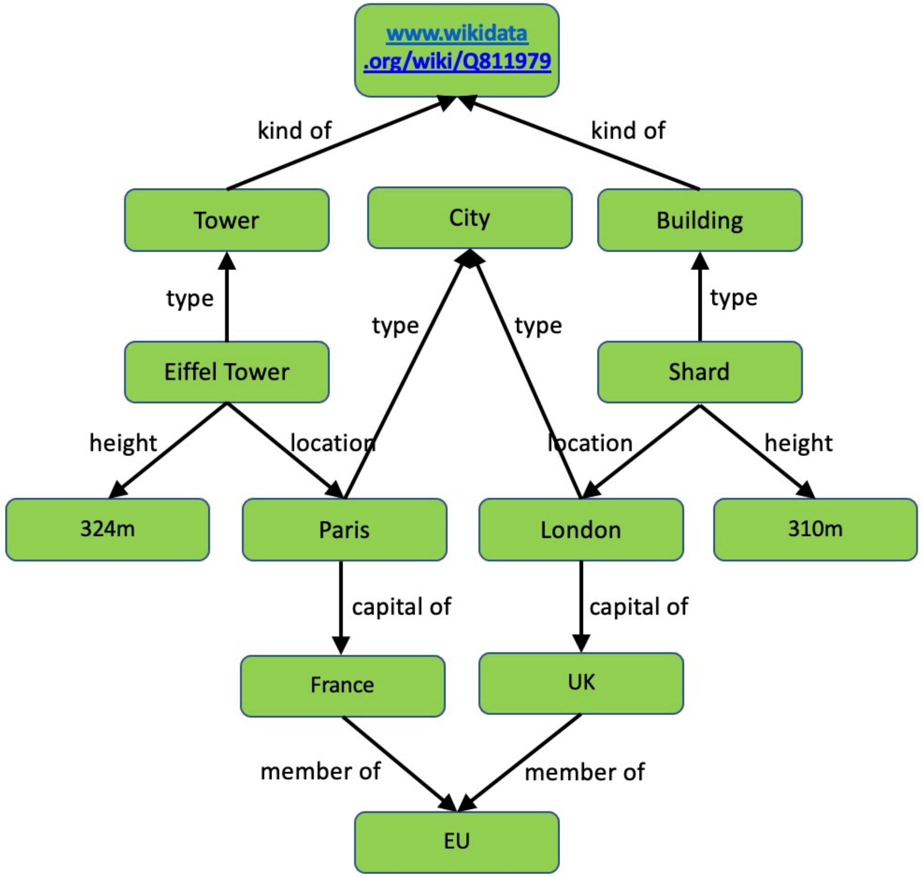

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- ✓ URIs not strings

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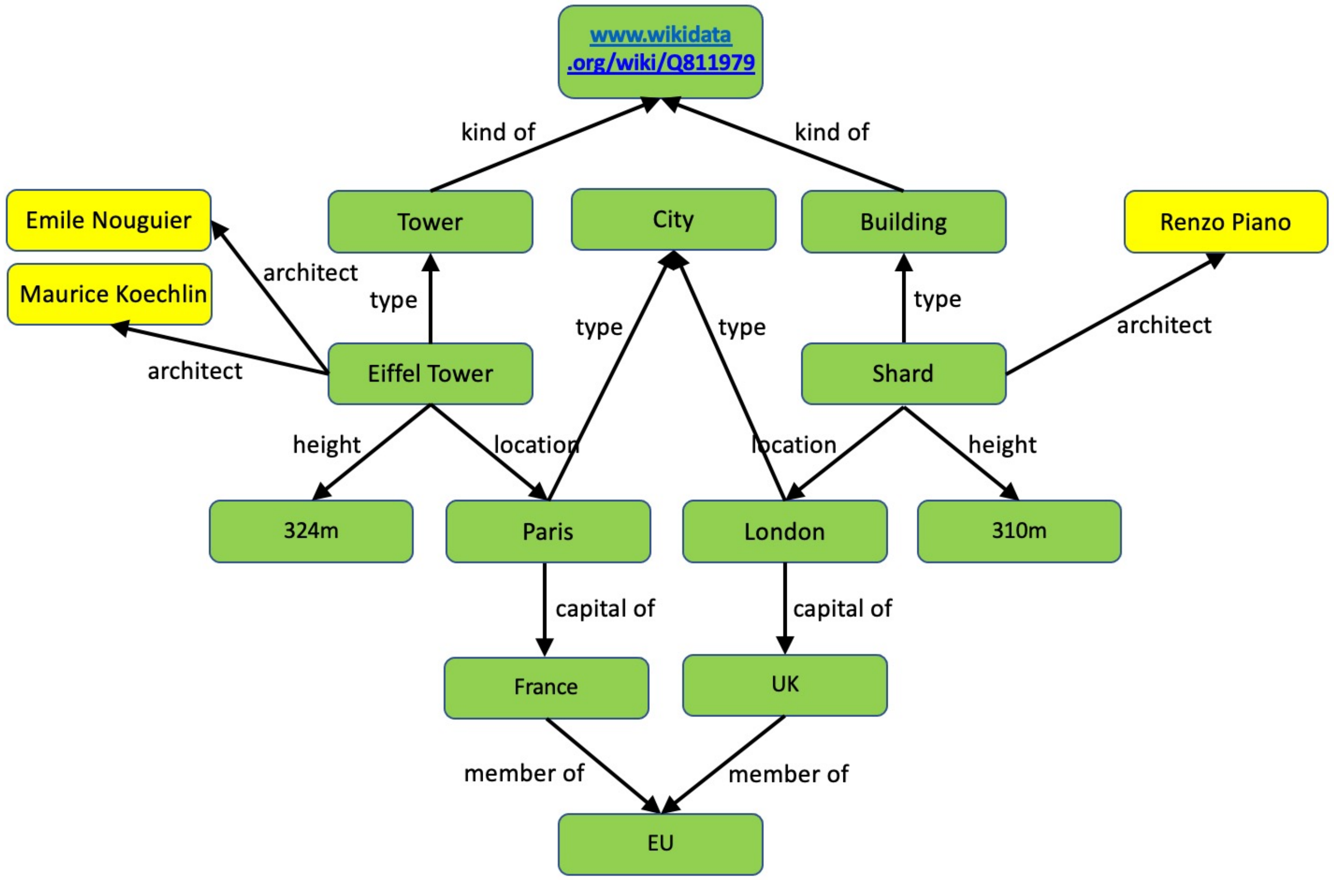

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- ✓ URIs not strings
- ✓ Flexible & extensible

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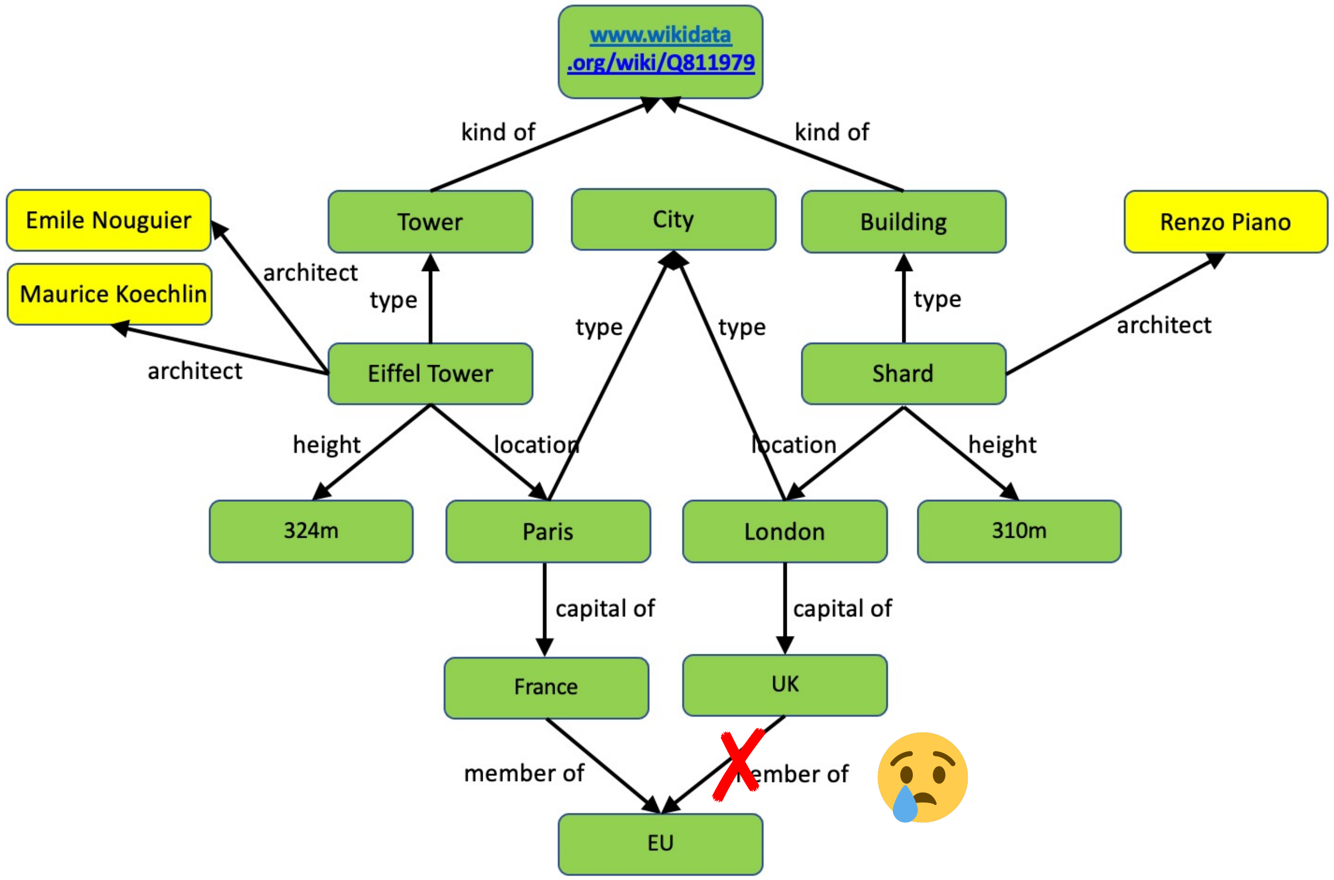

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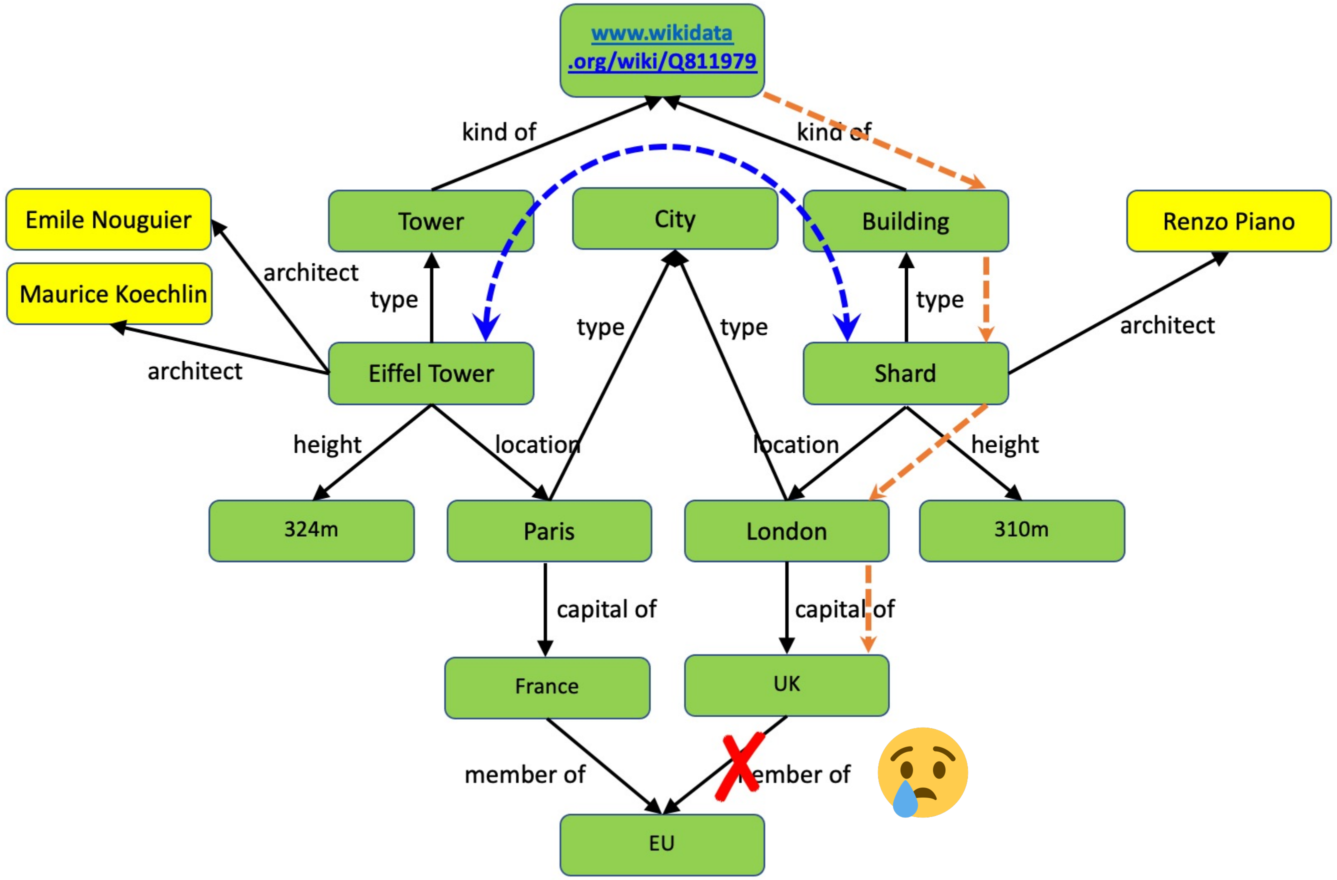
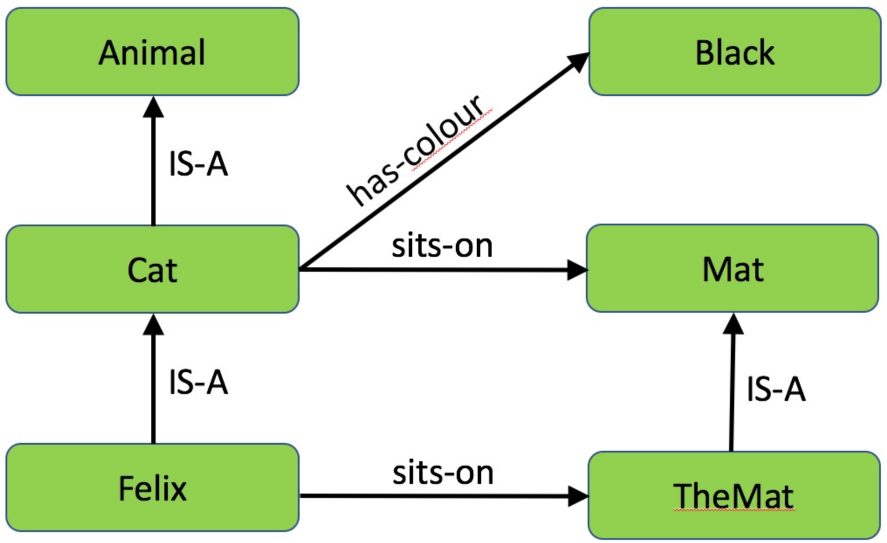


- ✓ Intuitive (e.g., no “foreign keys”)
- ✓ **Data** + **schema (ontology)**
- ✓ URIs not strings
- ✓ Flexible & extensible
- ✓ Other kinds of query
  - navigation
  - similarity & locality

Challenges and Solutions (1)

Vague Semantics



[Quillian, 1967]

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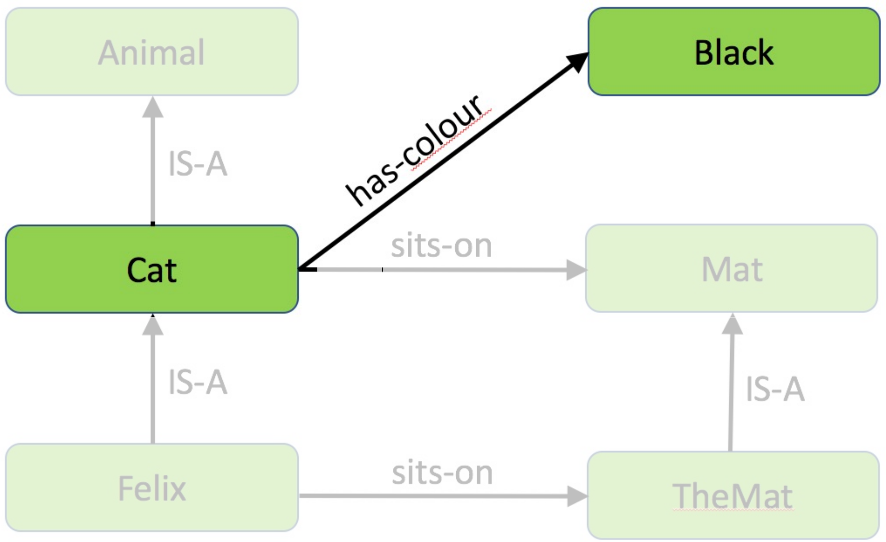

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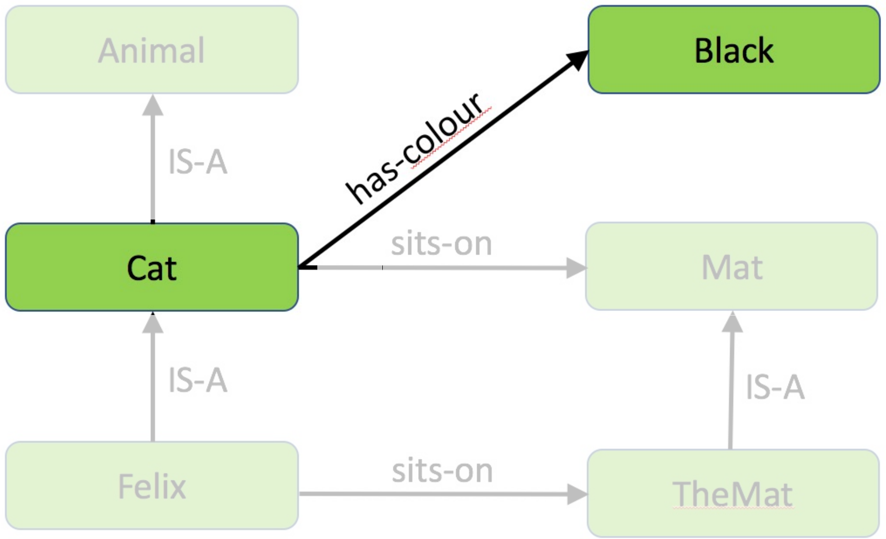

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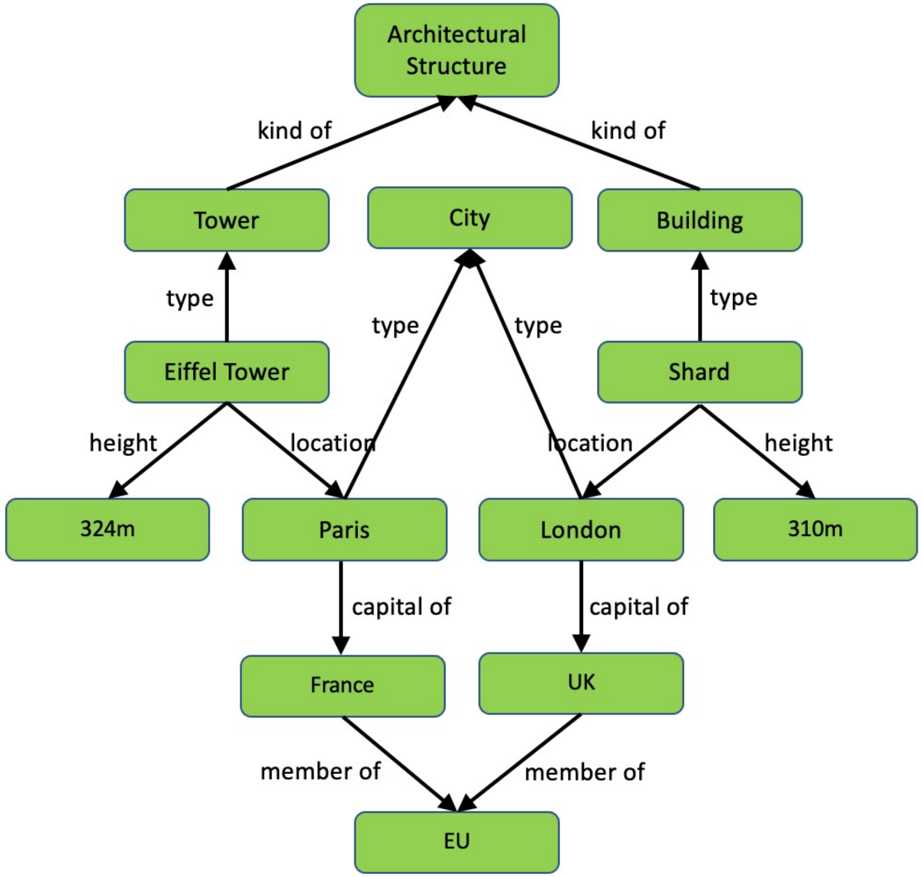
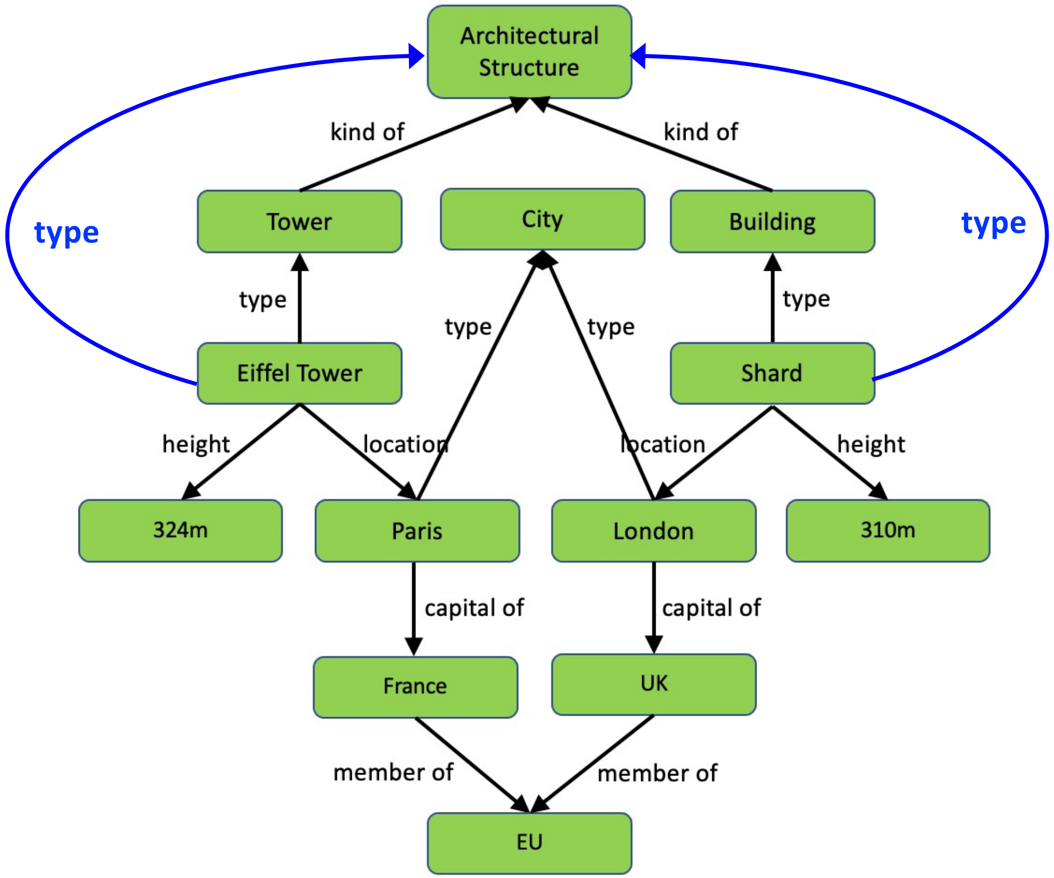


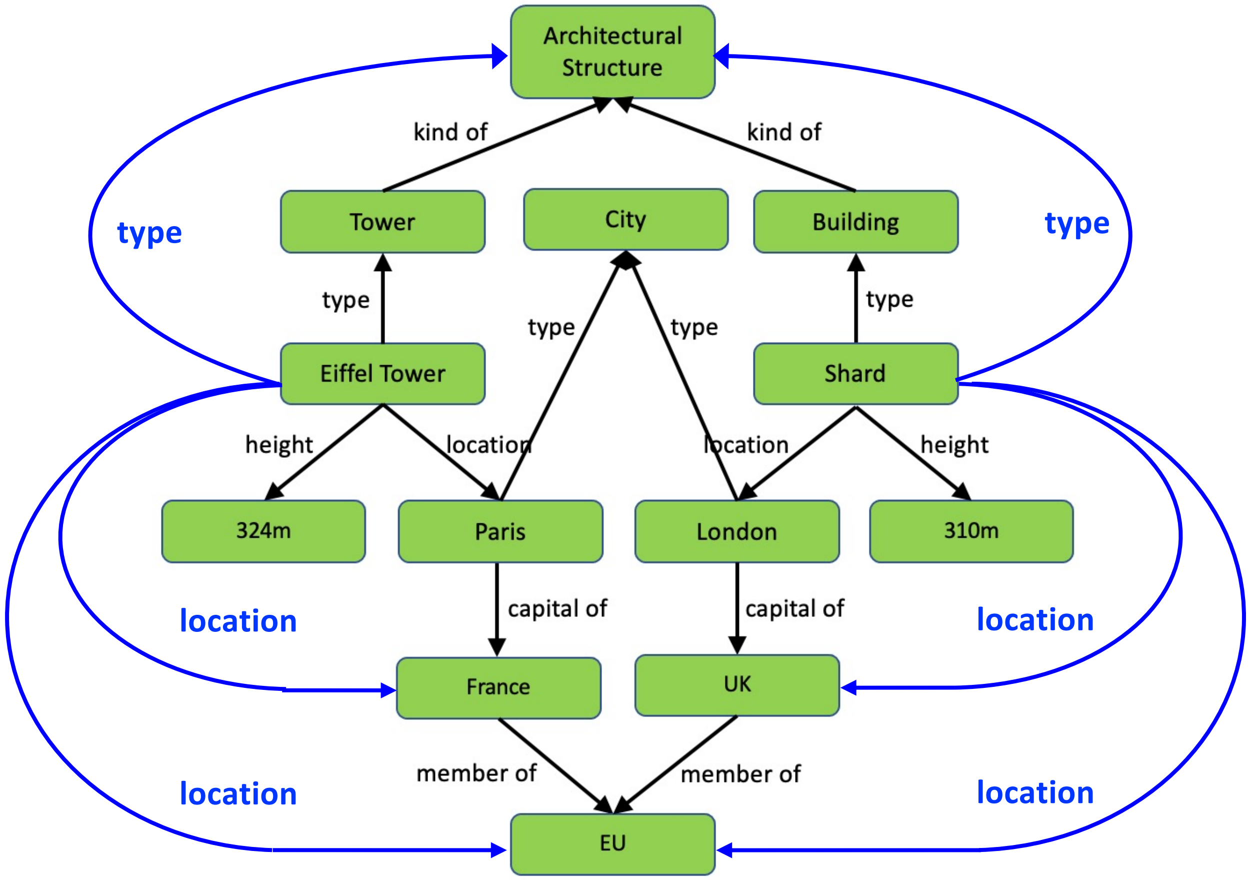
- Architectural Structure with location in the EU?

Vague Semantics



- Architectural Structure with location in the EU?
- Semantics of type and kind of edges?

Vague Semantics

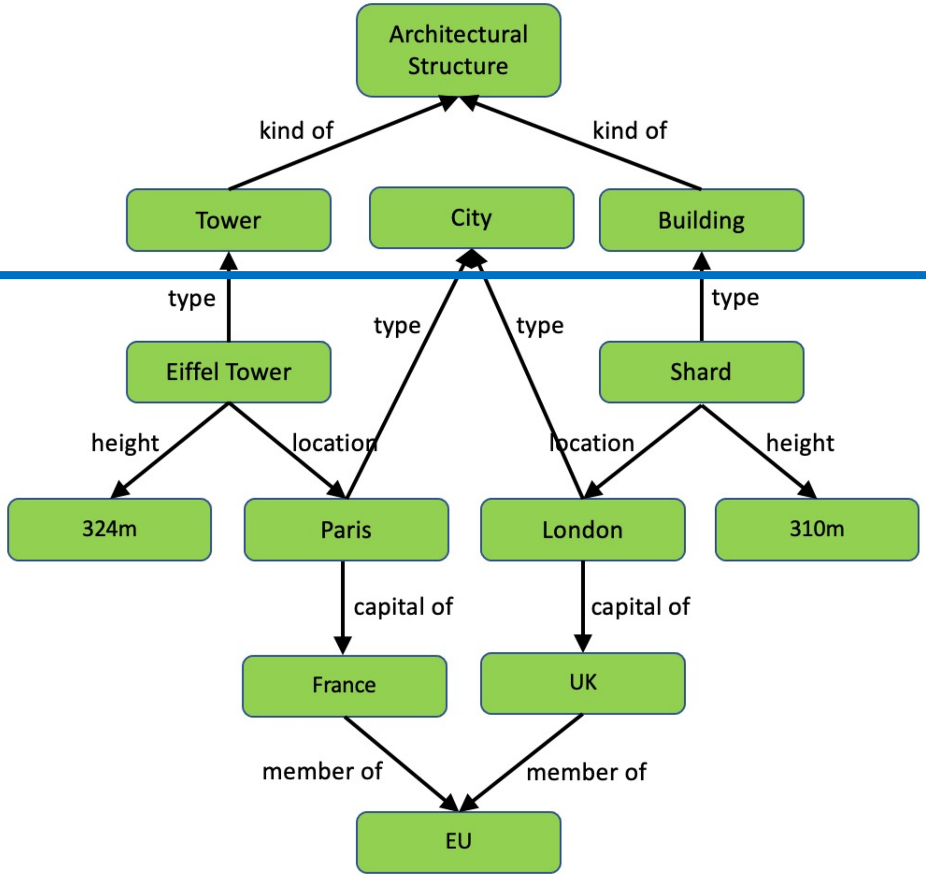


- Architectural Structure with location in the EU?
- Semantics of type and kind of edges?
- Semantics of location + capital of + member of edges?

Solution: Logic!

(OWL) ontology / conceptual schema

$\forall x\ \text{Tower}(x) \rightarrow \text{ArchitecturalStructure}(x)$
$\forall x\ \text{Building}(x) \rightarrow \text{ArchitecturalStructure}(x)$



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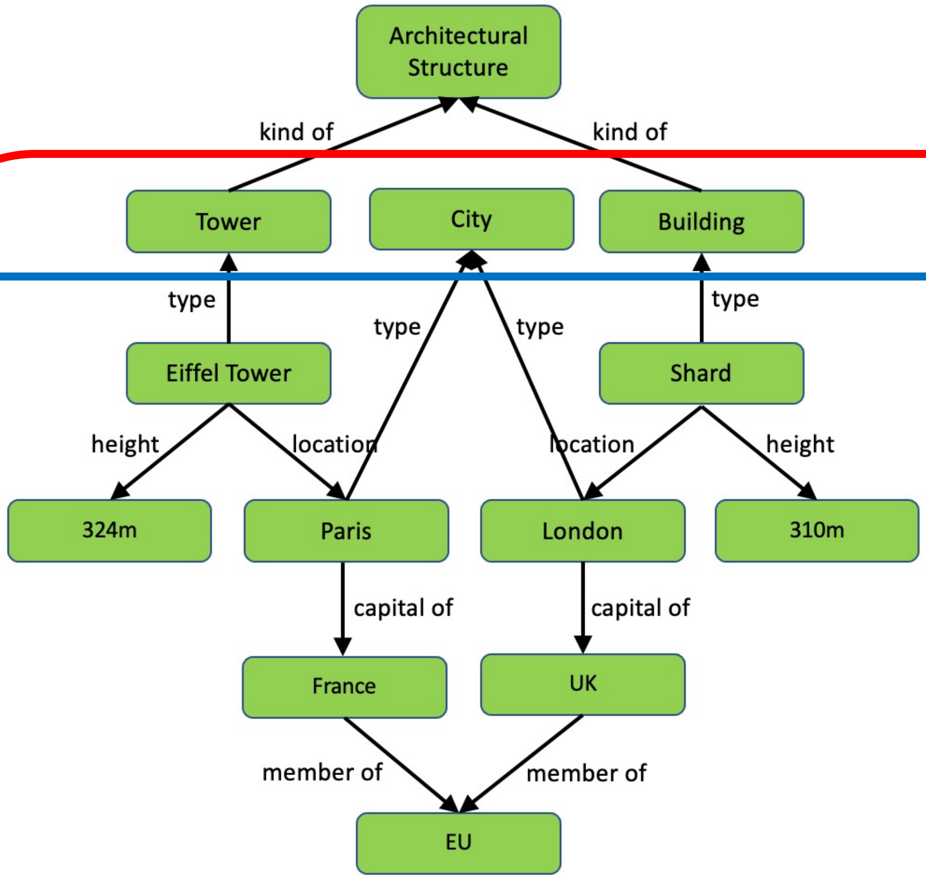
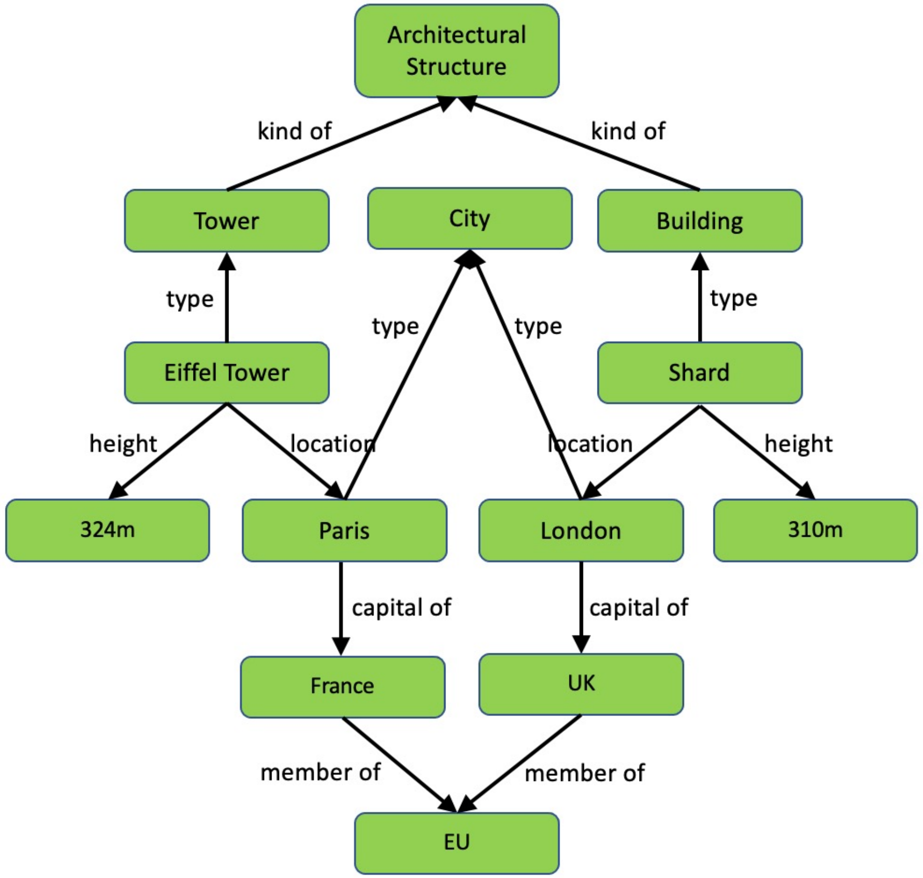


Tower(EiffelTower)	Building(Shard)
City(Paris)	City(London)
location(EiffelTower, Paris)	height(EiffelTower, 324m)
location(Shard, London)	height(Shard, 310m)
capital_of(Paris, France)	capital_of(London, UK)
member_of(France, EU)	member_of(UK, EU)

(RDF) graph / facts / data

Solution: Logic!

Knowledge base/graph



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$\mathsf{Tower}(\mathsf{EiffelTower})$	$\mathsf{Building}(\mathsf{Shard})$
$\mathsf{City}(\mathsf{Paris})$	$\mathsf{City}(\mathsf{London})$
$\mathsf{location}(\mathsf{EiffelTower}, \mathsf{Paris})$	$\mathsf{height}(\mathsf{EiffelTower}, \mathsf{324m})$
$\mathsf{location}(\mathsf{Shard}, \mathsf{London})$	$\mathsf{height}(\mathsf{Shard}, \mathsf{310m})$
$\mathsf{capital\_of}(\mathsf{Paris}, \mathsf{France})$	$\mathsf{capital\_of}(\mathsf{London}, \mathsf{UK})$
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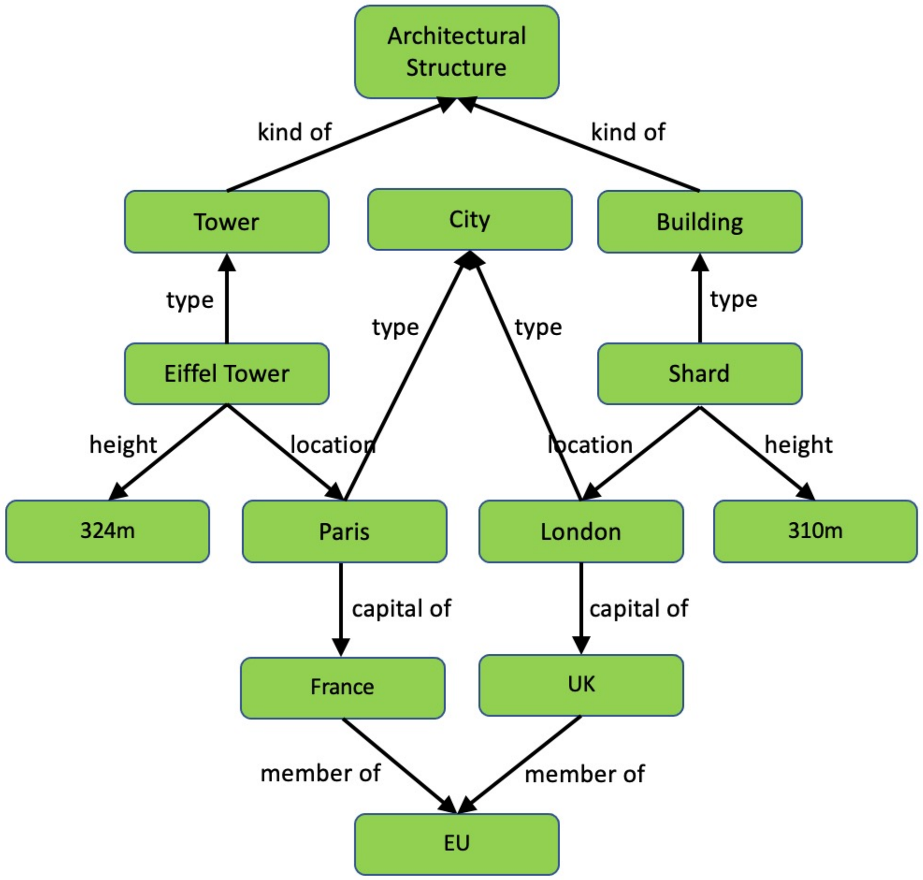
Solution: Logic!

Knowledge base/graph



$\forall x$ Tower$(x) \rightarrow$ ArchitecturalStructure(x)
$\forall x$ Building$(x) \rightarrow$ ArchitecturalStructure(x)
$\forall x, y, z$ location$(x, y) \wedge$ capital_of$(y, z) \rightarrow$ location(x, z)
$\forall x, y, z$ location$(x, y) \wedge$ member_of$(y, z) \rightarrow$ location(x, z)

Tower(EiffelTower)
City(Paris)
location(EiffelTower, Paris)
location(Shard, London)
capital_of(Paris, France)
member_of(France, EU)

Building(Shard)
City(London)
height(EiffelTower, 324m)
height(Shard, 310m)
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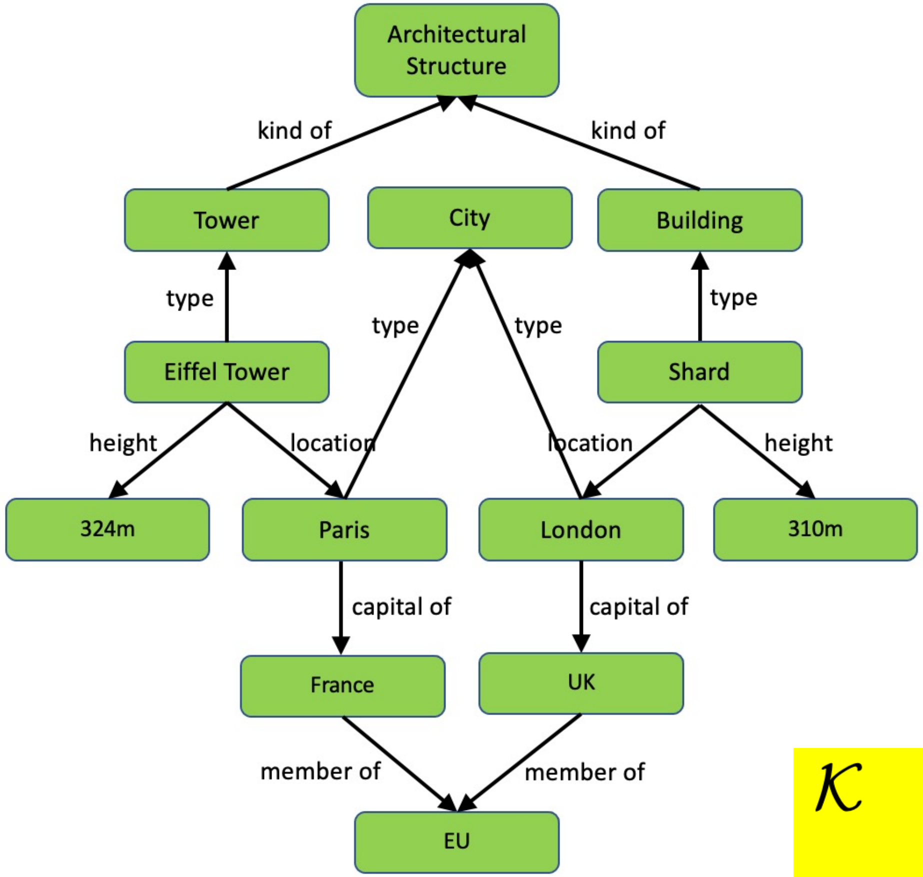
Solution: Logic!

Knowledge base/graph



$\forall x\ \text{Tower}(x) \rightarrow \text{ArchitecturalStructure}(x)$
$\forall x\ \text{Building}(x) \rightarrow \text{ArchitecturalStructure}(x)$
$\forall x, y, z\ \text{location}(x, y) \wedge \text{capital\_of}(y, z) \rightarrow \text{location}(x, z)$
$\forall x, y, z\ \text{location}(x, y) \wedge \text{member\_of}(y, z) \rightarrow \text{location}(x, z)$

Tower(EiffelTower)	Building(Shard)
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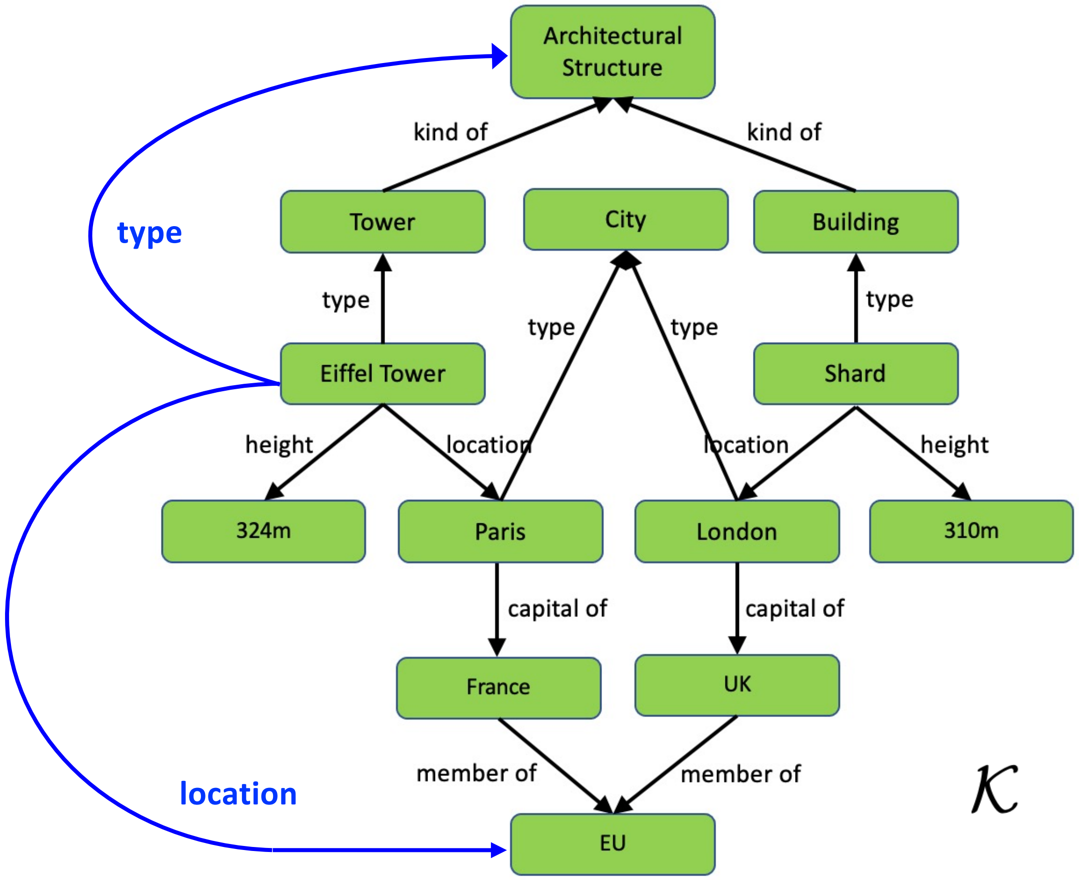
location(EiffelTower, Paris)	height(EiffelTower, 324m)
location(Shard, London)	height(Shard, 310m)
capital_of(Paris, France)	capital_of(London, UK)
member_of(France, EU)	member_of(UK, EU)

$$\mathcal{K} \models \text{ArchitecturalStructure}(\text{EiffelTower}) \wedge \text{location}(\text{EiffelTower}, \text{EU})$$

Solution: Logic!

Knowledge base/graph



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$\forall x, y, z$ location$(x, y) \wedge$ capital_of$(y, z) \to$ location(x, z)
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Tower(EiffelTower)
City(Paris)
location(EiffelTower, Paris)
location(Shard, London)
capital_of(Paris, France)
member_of(France, EU)

Building(Shard)
City(London)
height(EiffelTower, 324m)
height(Shard, 310m)
capital_of(London, UK)
member_of(UK, EU)

$\mathcal{K} \models$ ArchitecturalStructure(EiffelTower) $\wedge$
location(EiffelTower, EU)

Solution: Logic!

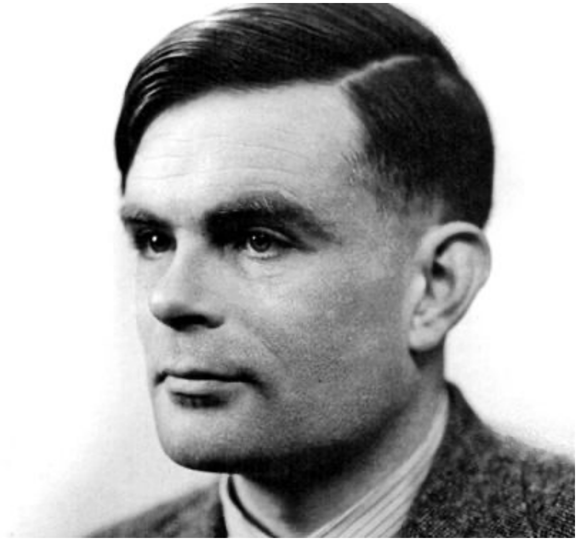
- Identify/devise algorithms that compute query answers
- E.g., using natural deduction rules:

$$\frac{\forall x P(x) \rightarrow Q(x) \quad P(a)}{Q(a)} \qquad \frac{\forall x\, \text{Building}(x) \rightarrow \text{ArchitecturalStructure}(x) \quad \text{Building}(\text{EiffelTower})}{\text{ArchitecturalStructure}(\text{EiffelTower})}$$

- Can check/prove algorithms are sound and complete w.r.t. semantics

Problem Solved?

- Some problems cannot be completely solved using standard computational model
  - halting problem
  - **FOL entailment problem**



- Even if decidable, reasoning might be of inherently high complexity and so take an infeasibly long time

So what to do?

- These are worst case results
  - Even if *logic* is undecidable, some *problems* may still be decidable
  - Even if *logic* is intractable, some *problems* may still be tractable

- **Study** KR languages to find suitable balance of expressive power and computability
- **Design** reasoning algorithms that work well in typical cases
- **Develop** highly optimised implementations

Description Logic

- Family of logic-based KR languages
- Most are decidable subsets of FOPC (usually in C2)
- Provide a range of different constructors
  - Booleans (and, or, not)
  - Restricted forms of quantification (exists, forall)
  - Counting (atmost, atleast)
  - …
- Decidability/complexity and (efficient) algorithms known for many combinations of constructors
- Effective reasoners available for several “sweet-spot” DLs

W3C and the Semantic Web

- Goal: to make web data machine-readable
  - KRR on the web
- Standardized **RDF**
  - Graphical data model for representing facts
- Extended RDF with **OWL**
  - Ontology language based on expressive DL (**SROIQ)**
- Developed **SPARQL** query language
  - Similar to SQL
  - Tailored to graphical data model

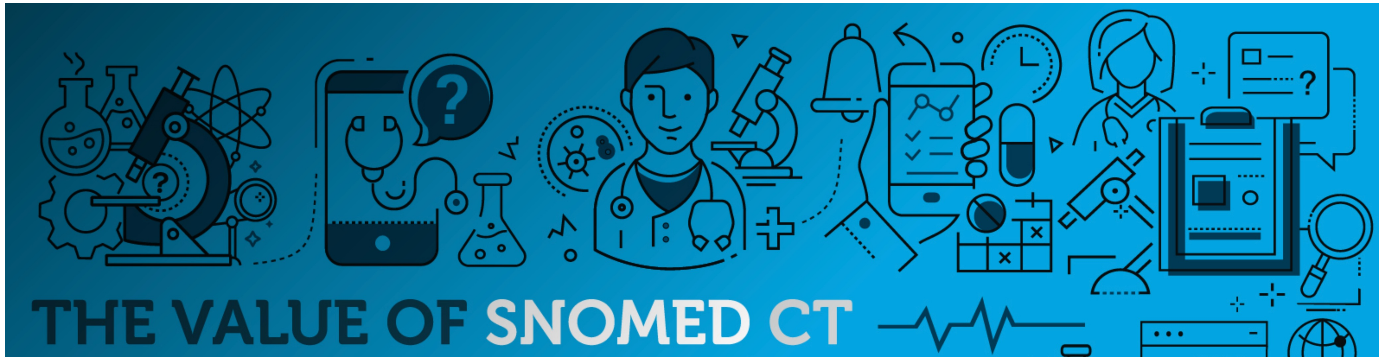
RDF

SPARQL

Challenges and Solutions (2)

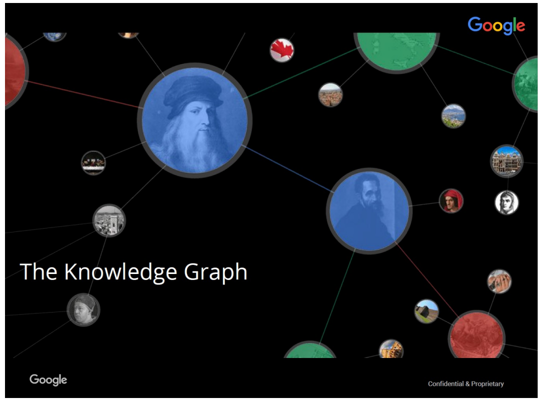
Ontology-centric Applications

- Development of large/complex ontologies
  - Class axioms (usually $<10^6$ classes) with few or no facts
  - Main reasoning task is consistency/subsumption
- OWL/DL reasoners such as **HermiT** and **ELK** used
  - to identify errors and inconsistencies
  - to compute class hierarchy (classification)
- Widely used in medicine and life sciences
  - Bioportal (900+ ontologies)
  - **SNOMED CT**
  - …



Data-centric Applications

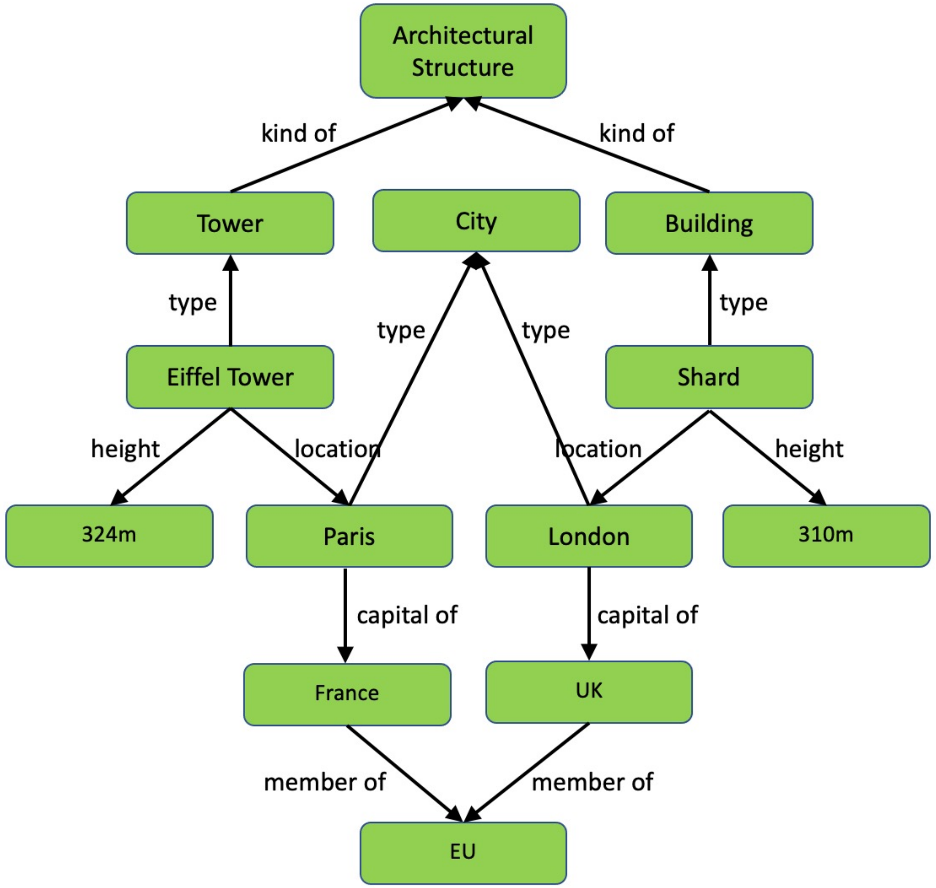
- Development and deployment of large knowledge graphs
  - Ontology/rules plus large number of facts (can be $>10^9$ edges)
  - Main reasoning task is (SPARQL) query answering
- OWL/DL reasoners don't scale well to this task
  - Query answering reduces to multiple entailment checks
  - Number of checks is polynomial in size of graph
  - Each such check can be costly



OWL 2 Profiles

- OWL 2 is based on powerful but still decidable DL (SROIQ)
- OWL 2 also introduced three “profiles” based on tractable subsets
  - **QL**: based on the DL-Lite description logic
  - **EL**: based on the EL description logic
  - **RL**: based on the DL fragment of Datalog (aka DLP)
- Profiles allow for algorithmic techniques suited to query answering
  - **Query rewriting** for QL
  - **Materialisation** for RL
  - **Combined approach** for EL

Materialisation for OWL RL



$$Q(x) \leftarrow \text{Architectural\_Structure}(x)$$

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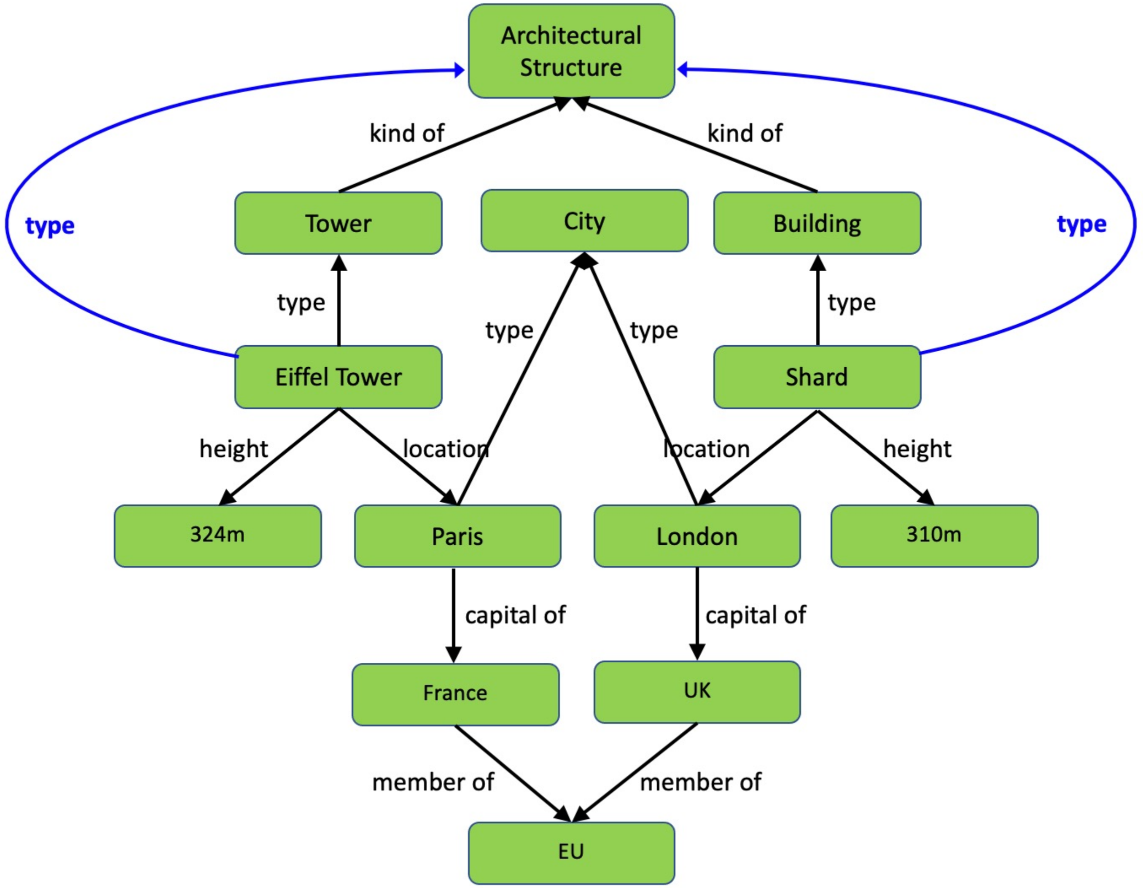

$$Q(x) \leftarrow \text{Architectural\_Structure}(x)$$

$$\text{Tower} \sqsubseteq \text{Architectural\_Structure}$$
$$\text{Building} \sqsubseteq \text{Architectural\_Structure}$$

$$\text{Tower}(x) \rightarrow \text{Architectural\_Structure}(x)$$
$$\text{Building}(x) \rightarrow \text{Architectural\_Structure}(x)$$

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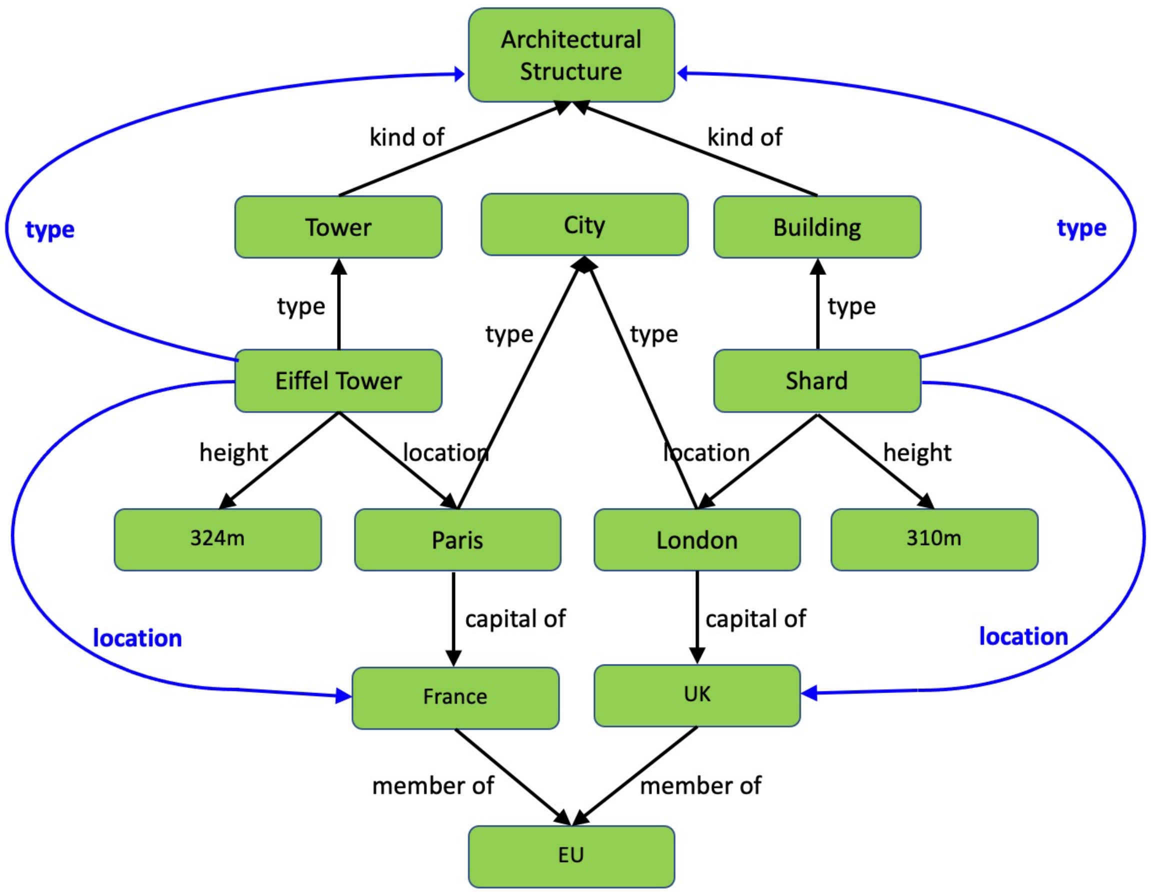

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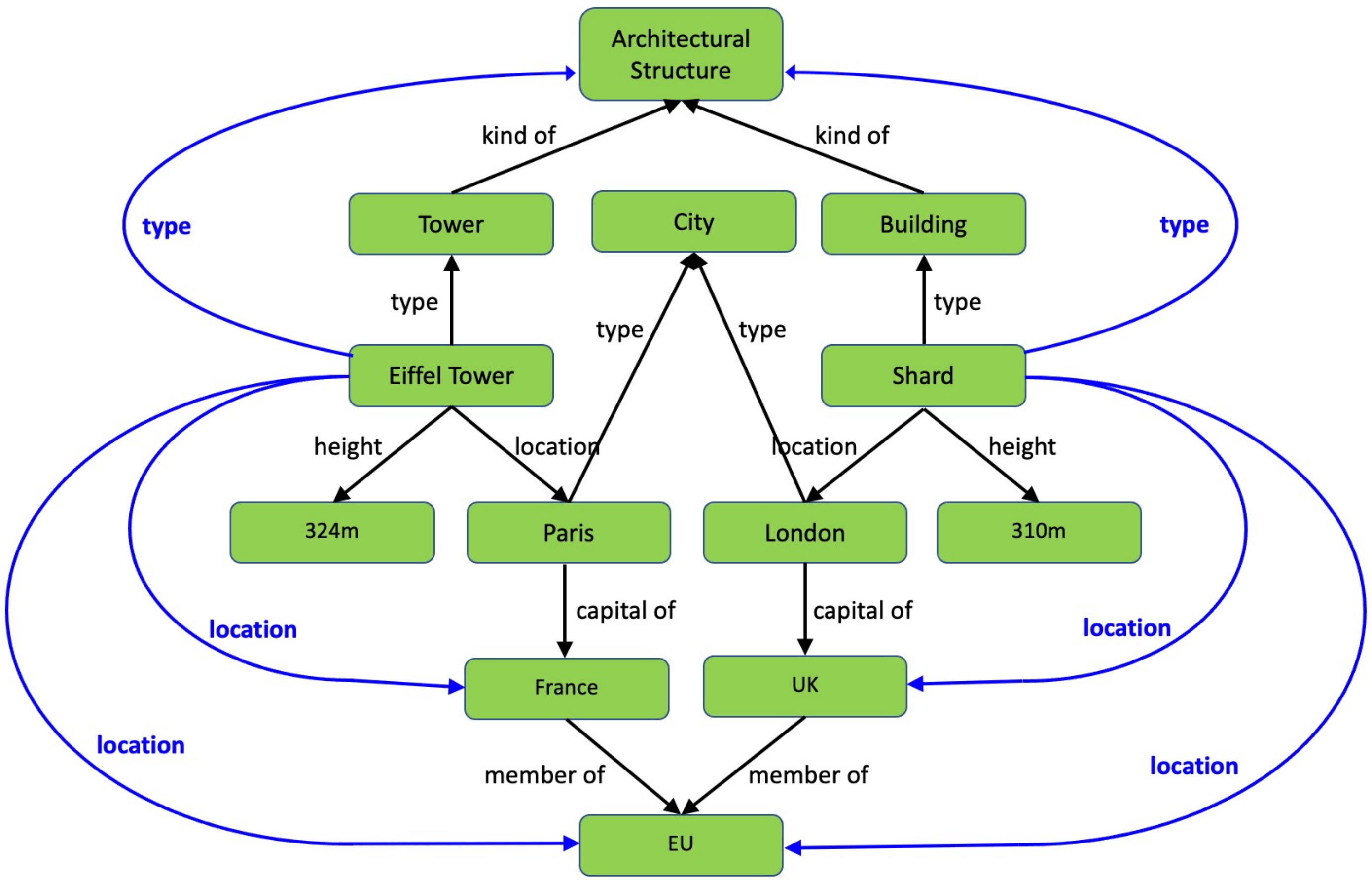

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$$\text{Tower} \sqsubseteq \text{Architectural\_Structure}$$
$$\text{Building} \sqsubseteq \text{Architectural\_Structure}$$

$$\text{Tower}(x) \rightarrow \text{Architectural\_Structure}(x)$$
$$\text{Building}(x) \rightarrow \text{Architectural\_Structure}(x)$$

$$\text{location}(x, y) \wedge \text{capital\_of}(y, z) \rightarrow \text{location}(x, z)$$

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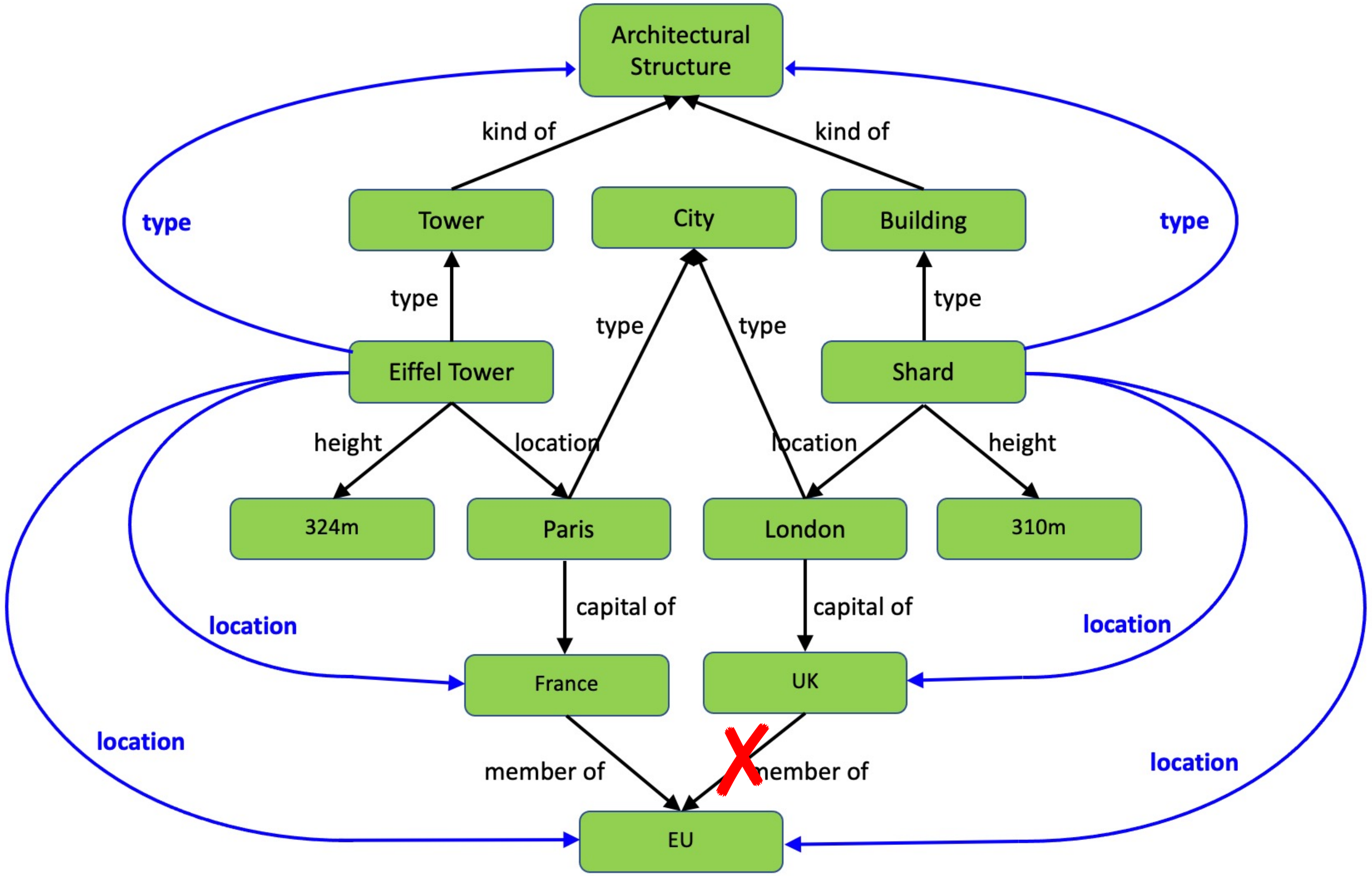
Materialisation for OWL RL



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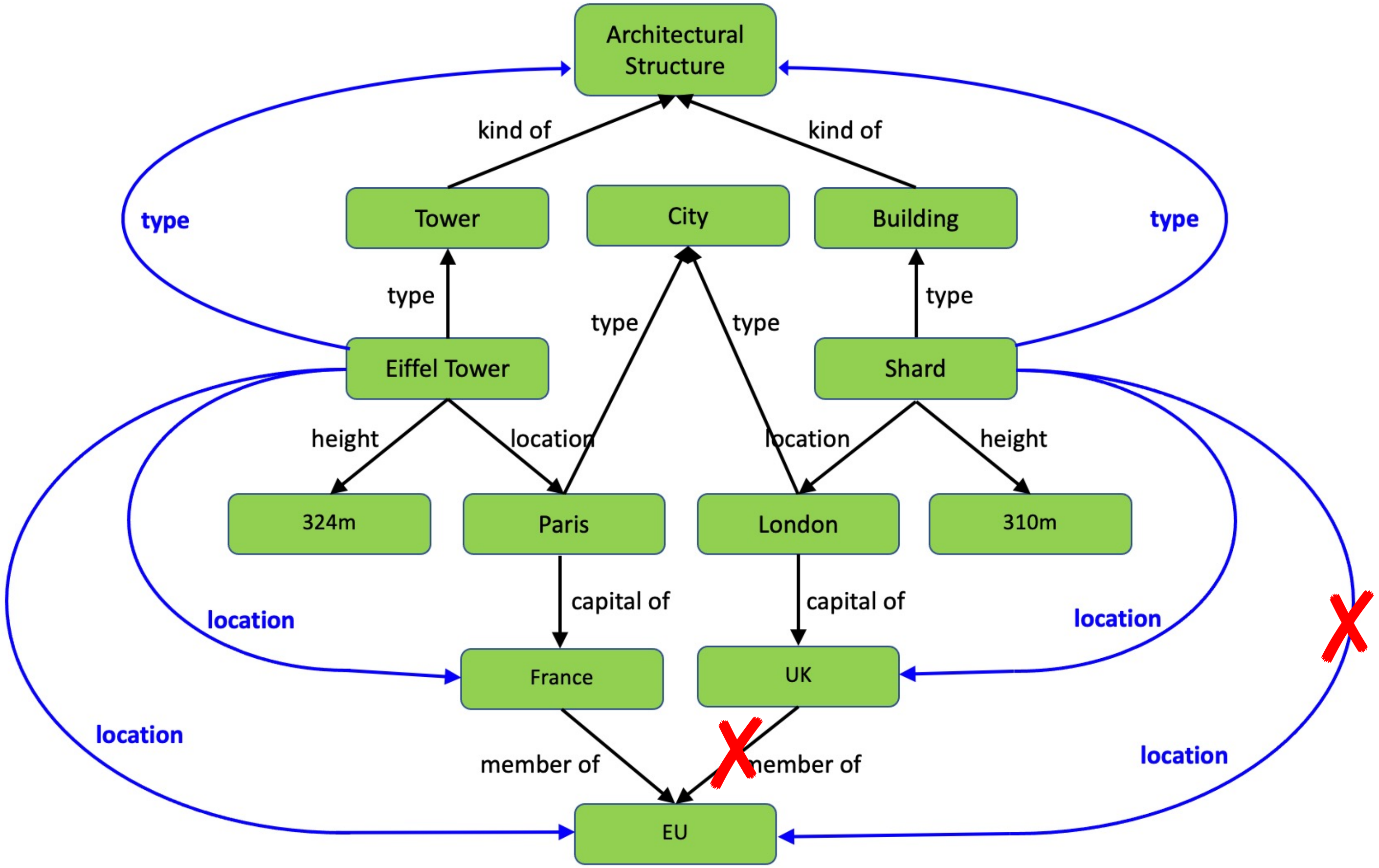

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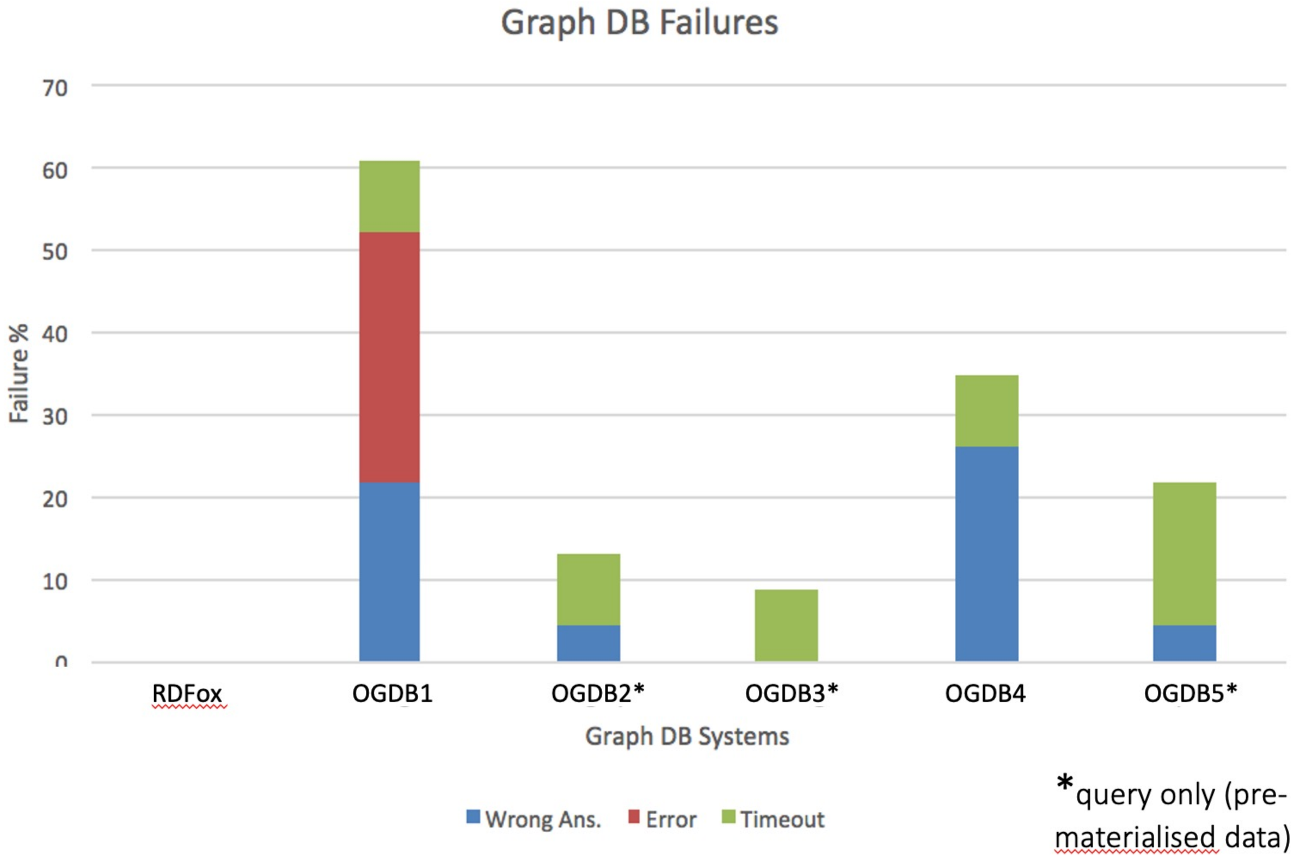
RDFOX

- Materialization reasoning seems ideal for data-centric applications
  - Can support expressive ontology languages
  - Fast query answering over very large graphs
- Challenges
  - Materialisation can be costly in time and memory
  - Materialisation may need to be repeated if data changes
- Solution: RDFox
  - Optimised materialization exploiting modern multi-core architectures
  - Incremental maintenance as data changes

RDFOX

- **Novel algorithms developed at Oxford**
  - Proven correctness



*query only (pre-materialised data)

RDFOX

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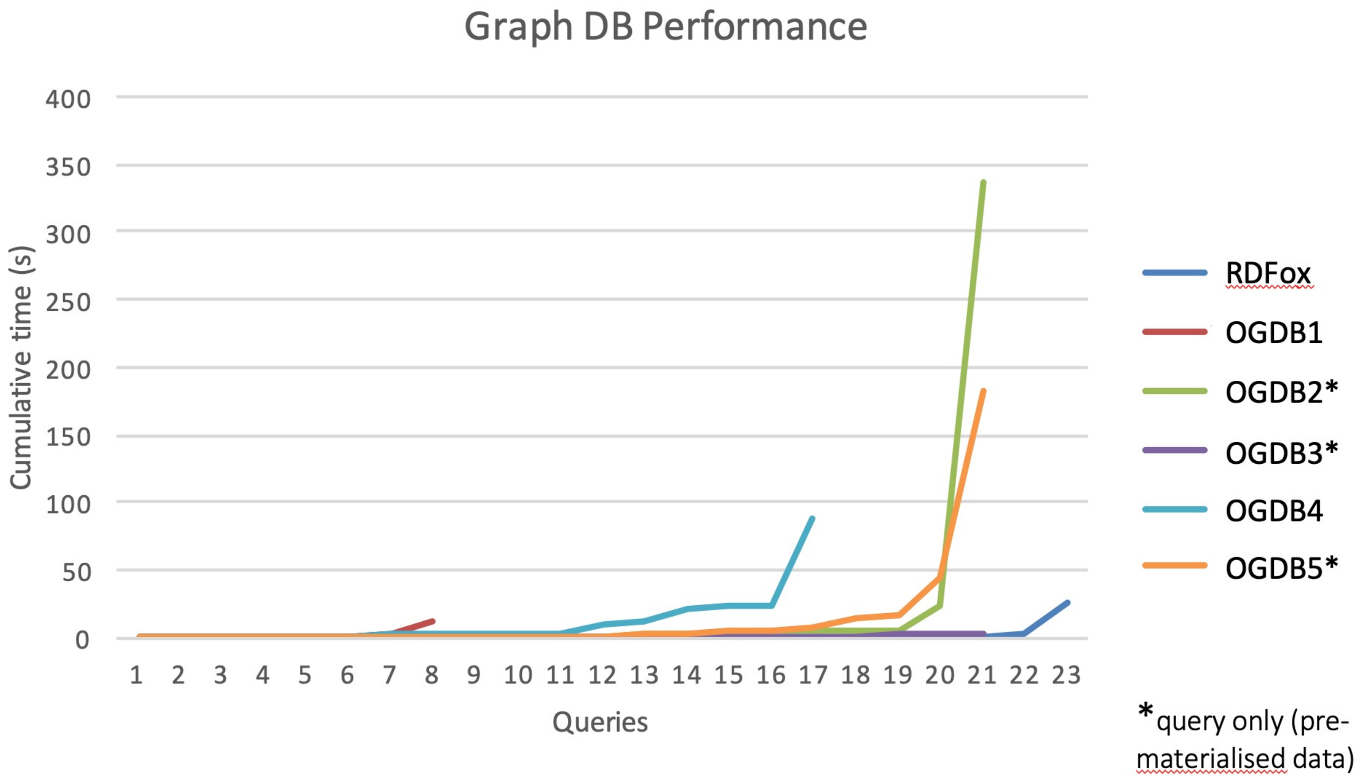

RDFOX

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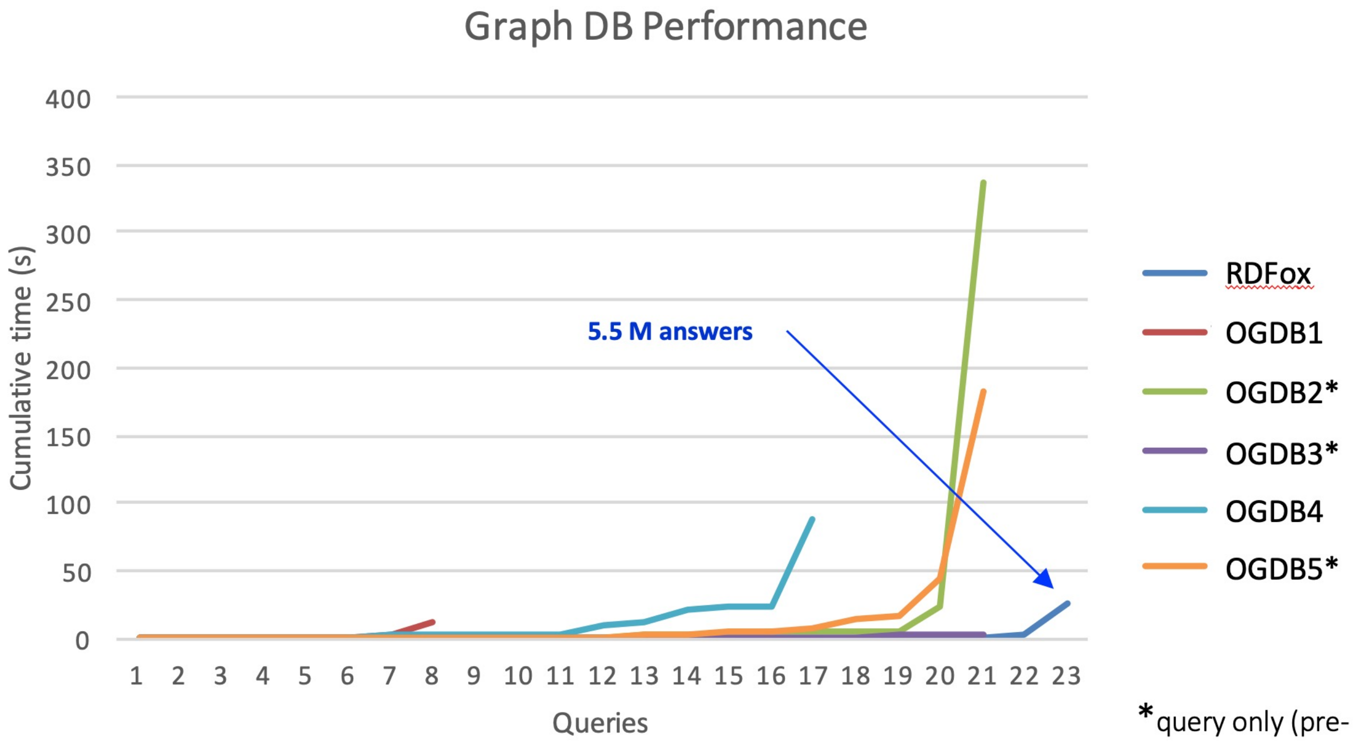

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RDFOX

- **Novel algorithms developed at Oxford**
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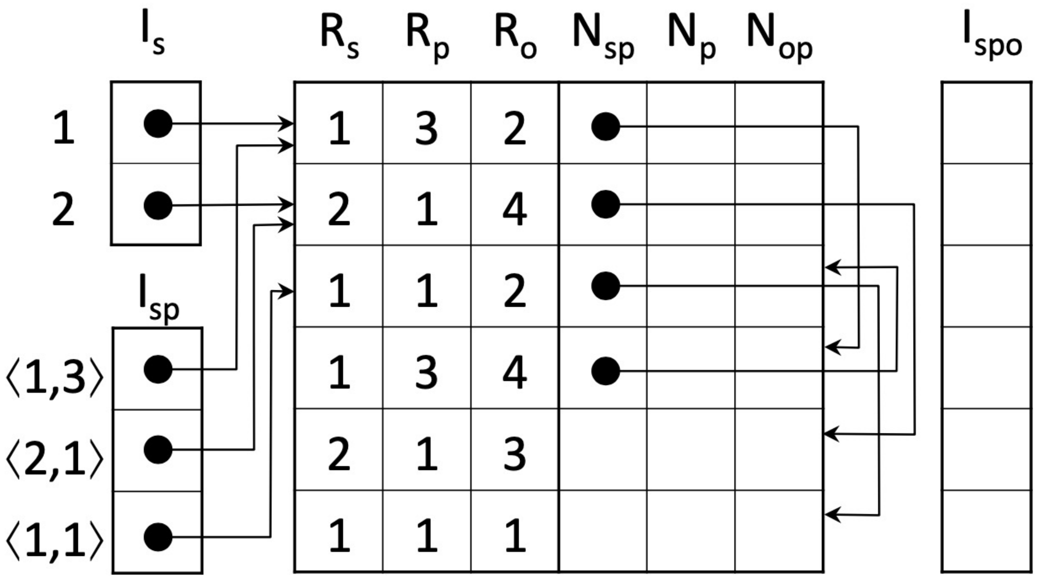
- **Optimized in-memory data structures**
  - >10^9 triples on 128 Gb entry level server
  - >10^{10} triples on 1 Tb server



RDFOX

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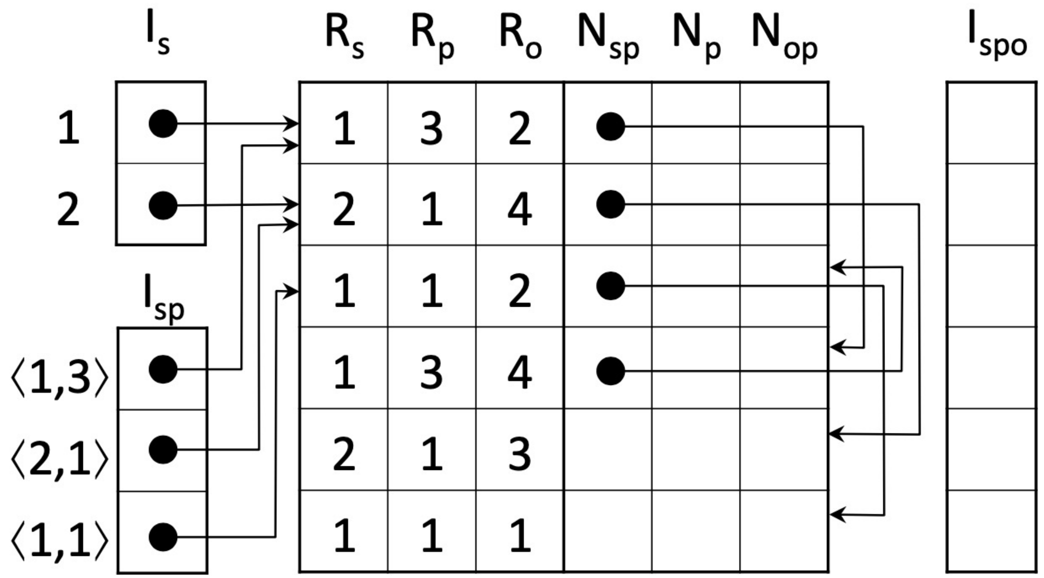
- **Parallelised materialisation**
  - Dynamic distribution of workload
  - Mostly lock-free data structures



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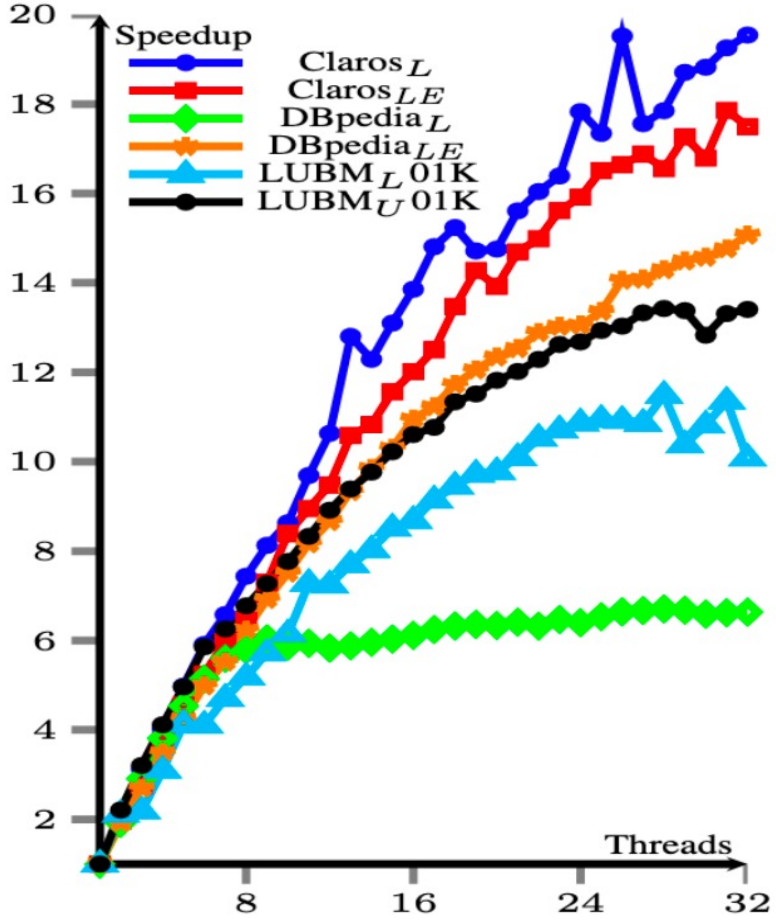

RDFOX

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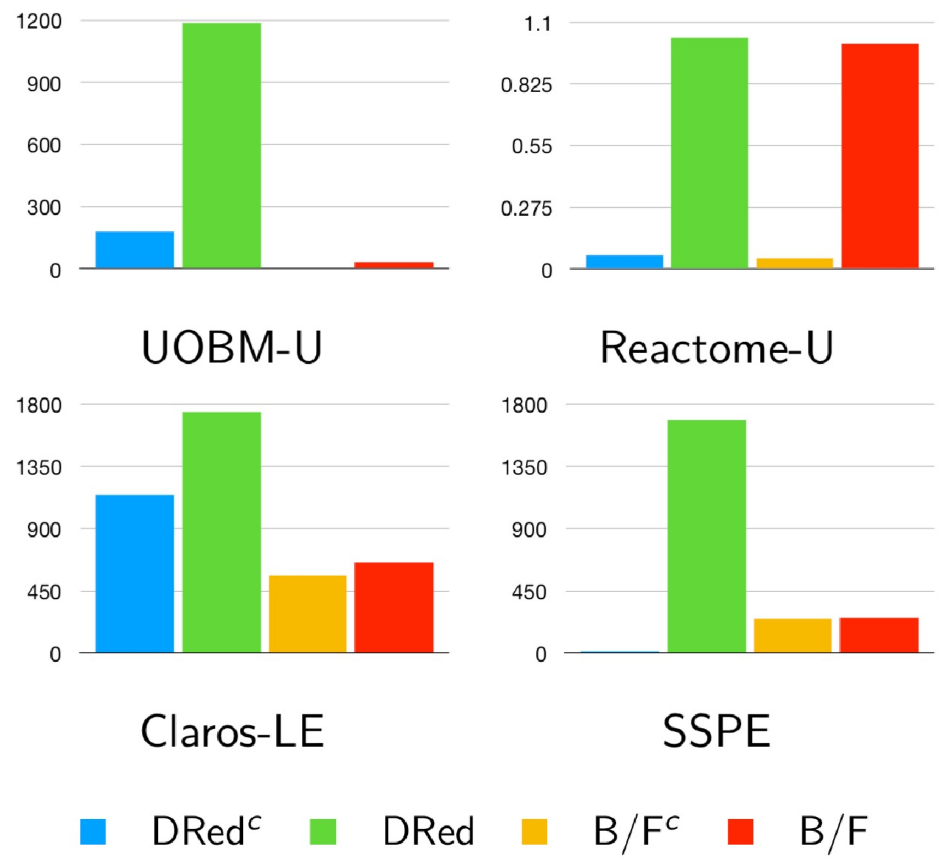
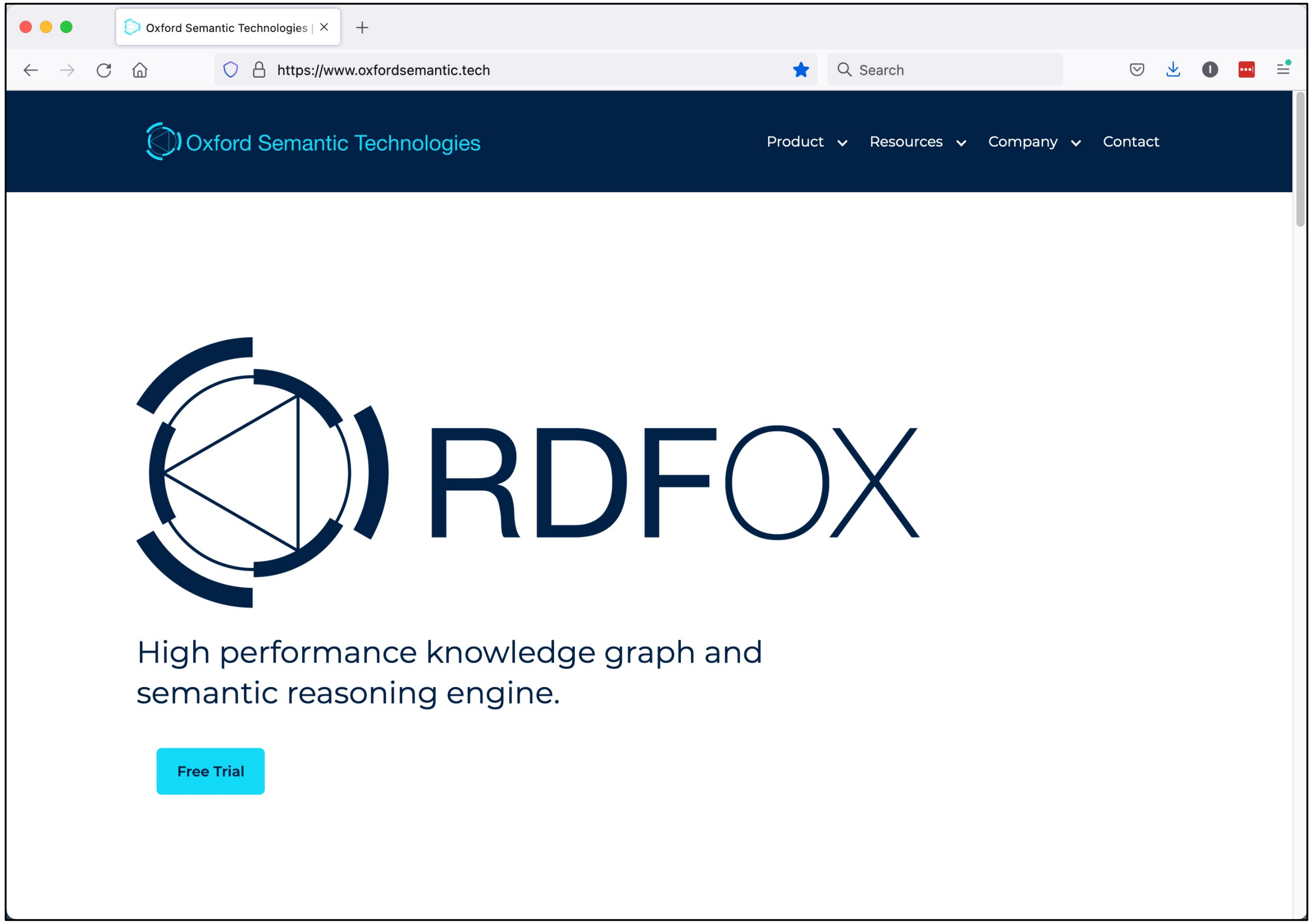
- **Parallelised materialisation**
  - Dynamic distribution of workload
  - Mostly lock-free data structures
- **Incremental addition and retraction**
  - Novel B/F materialisation maintenance algorithm



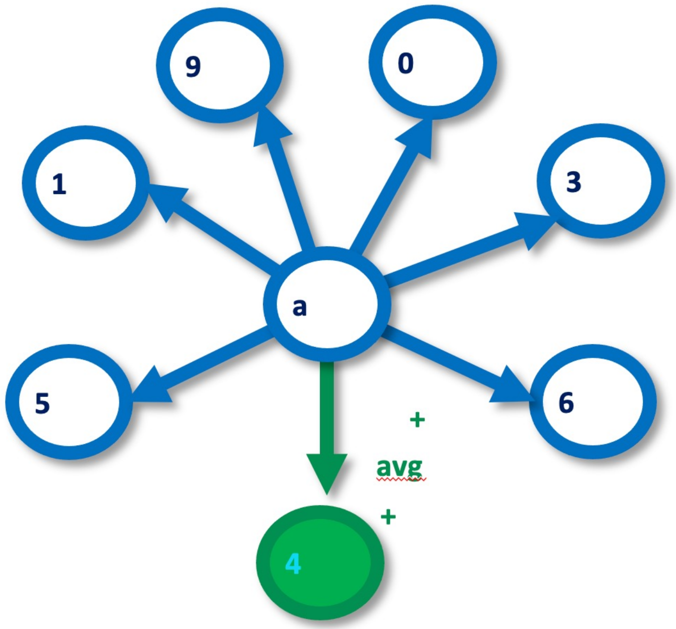
Challenges and Solutions (3)

Oxford Semantic Technologies

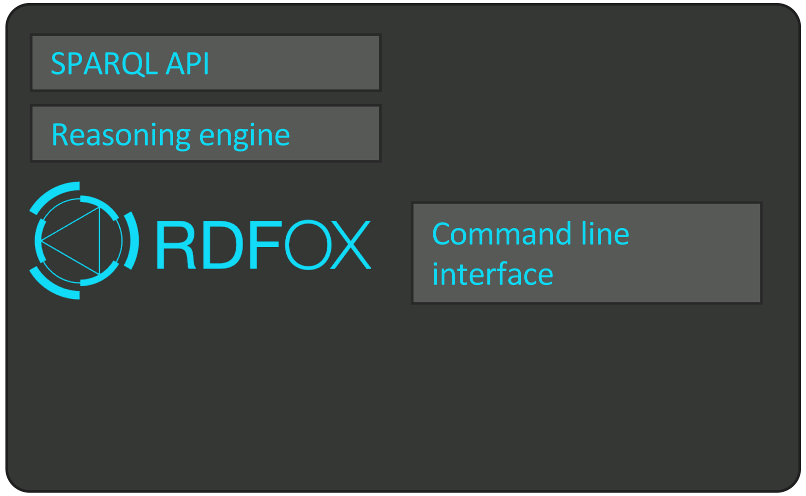


Extensions

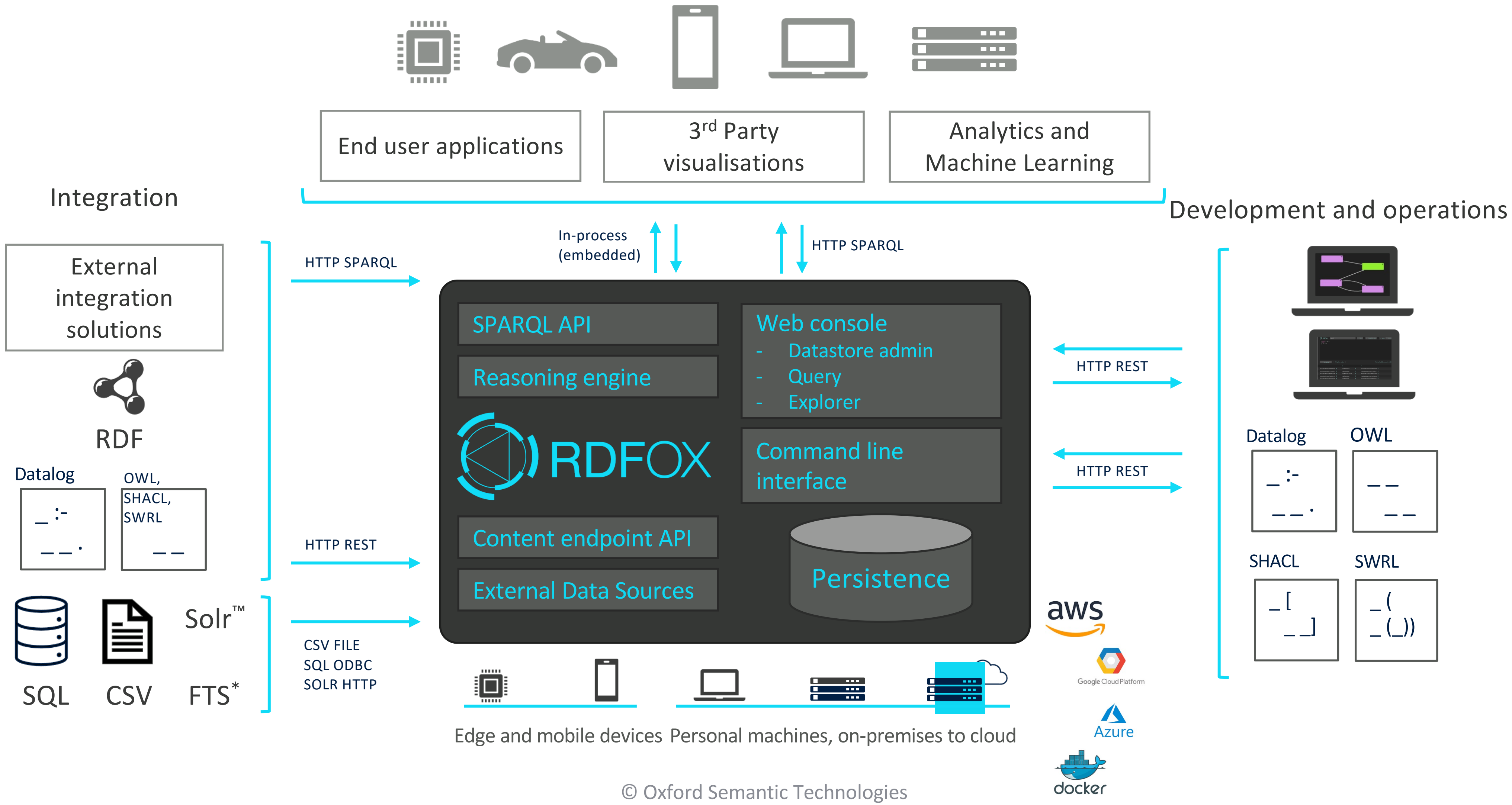
- Arbitrary rules
  - No restriction to OWL RL (tree-shaped) rules
- Data types and values
  - Numbers, strings, dates, …
  - Built in functions and aggregation
- Value invention
  - Add new (possibly computed) values to graph
  - Add new URI nodes to graph
- Constraints and negation as failure
  - SHACL+



System Architecture



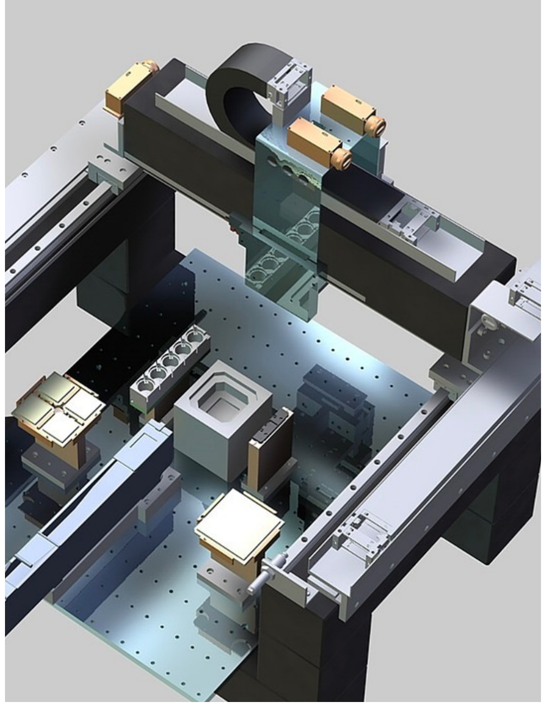
System Architecture

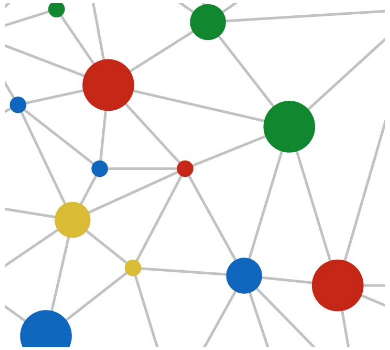


Knowledge Graph Use Cases

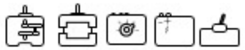
Configuration Management

FESTO

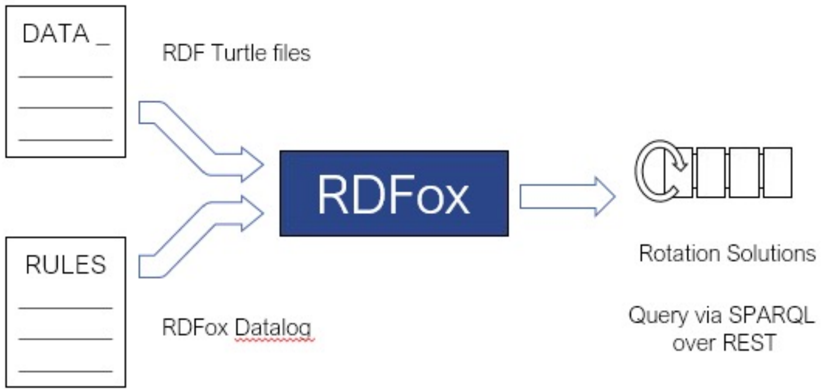


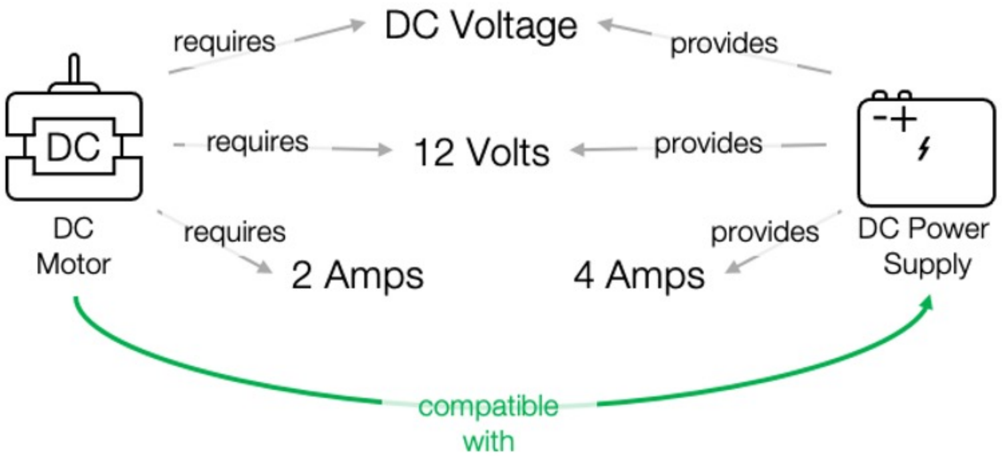


- Components
- Their attributes & constraints



- Definitions of compatibility &
- Valid configurations





Oxford Semantic Technologies

Wrap-up

Summary

- **KGs are powerful tool** for representing & reasoning about knowledge
- **Many applications**: configuration, data integration, compliance, …
- **Technical challenges**: complexity, scalability, extensions, systems, …
- **Solutions** based on foundational research + systems engineering

Thanks to Colleagues Collaborators and Funders

EPSRC
Engineering and Physical Sciences Research Council

EU

DARPA

SAMSUNG

SIEMENS

ebay

eDF

ORACLE

Thanks for Listening
Any Questions?

RDFOX : **www.oxfordsemantic.tech**

Background reading:

- **Description Logic:** Baader, Horrocks, Lutz, and Sattler. *An Introduction to Description Logic*. Cambridge University Press, 2017.
- **OWL:** Horrocks, Patel-Schneider, and van Harmelen. *From SHIQ and RDF to OWL: The Making of a Web Ontology Language*. J. of Web Semantics, 1(1):7-26, 2003.
- **RDFox algorithms & data structures:** Motik, Nenov, Piro, Horrocks, and Olteanu. *Parallel Materialisation of Datalog Programs in Centralised, Main-Memory RDF Systems*. AAAI 2014.
- **Incremental maintenance:** Motik, Nenov, Robert Piro, and Horrocks. *Maintenance of datalog materialisations revisited*. Artificial Intelligence, 269:76-136, 2019.