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# Reasoning and Querying with Knowledge Graphs

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Lecturer in Artificial Intelligence

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# Before we start...

# GitHub Repository

`https://github.com/city-knowledge-graphs/phd-course`



# Agenda

- Four sessions split into two days
- **Morning sessions:**
  - Theory: 9:00-10:30
  - Break 15 min
  - Hands-on: 10:45-12:15
- Lunch break (1hour)
- **Afternoon sessions:**
  - Theory: 13:15-14:45
  - Break 15 min
  - Hands-on: 15:00-16:30

# Course Organization

- ✓ Introduction to Knowledge Graphs
  - ✓ Lab: Creation of a small knowledge graph and ontology.
- 2. Reasoning and Querying with Knowledge Graphs
  - Lab: First steps with the SPARQL query language.
- 3. Matching: KG-to-KG and CSV-to-KG
  - Lab: Creation of a (simple) matching system.
- 4. Knowledge Graphs and Language Models
  - Lab: Ontology Embeddings with OWL2Vec\*.

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# PART I: SPARQL Query Language for RDF-based KGs

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## SPARQL by Example

# SPARQL

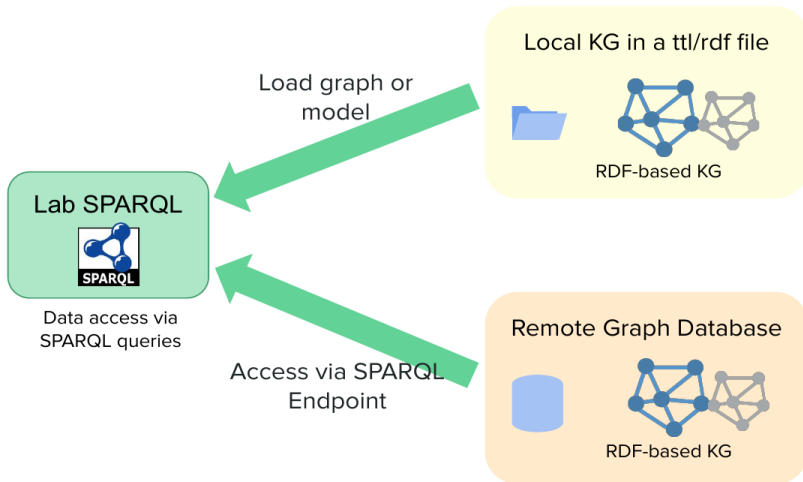
- SPARQL Protocol And RDF Query Language
- **Standard language** to query graph data represented as **RDF triples**
- W3C Recommendations
  - **SPARQL 1.0**: W3C Recommendation 15 January 2008
  - **SPARQL 1.1**: W3C Recommendation 21 March 2013



# SPARQL

- SPARQL Protocol And RDF Query Language
- **Standard language** to query graph data represented as **RDF triples**
- W3C Recommendations
  - **SPARQL 1.0**: W3C Recommendation 15 January 2008
  - **SPARQL 1.1**: W3C Recommendation 21 March 2013
- Documentation:
  - Syntax and semantics of the SPARQL query language for RDF:  
<http://www.w3.org/TR/rdf-sparql-query/>  
<https://www.w3.org/TR/sparql11-overview/>
  - Examples: <https://www.w3.org/2008/09/sparql-by-example/>

# SPARQL: local and remote KG access



## SPARQL Examples (i)

- Based on DBpedia: RDF version of Wikipedia with information about actors, movies, etc.: <https://dbpedia.org/>
- Web interface for SPARQL writing: <http://dbpedia.org/sparql>

## SPARQL Examples (i)

- Based on DBpedia: RDF version of Wikipedia with information about actors, movies, etc.: <https://dbpedia.org/>
- Web interface for SPARQL writing: <http://dbpedia.org/sparql>

### People called “Johnny Depp”

```
PREFIX foaf: <http://xmlns.com/foaf/0.1/>
SELECT DISTINCT ?jd WHERE {
    ?jd foaf:name "Johnny Depp"@en .
}
```

## SPARQL Examples (i)

- Based on DBpedia: RDF version of Wikipedia with information about actors, movies, etc.: <https://dbpedia.org/>
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### People called “Johnny Depp”

```
PREFIX foaf: <http://xmlns.com/foaf/0.1/>
SELECT DISTINCT ?jd WHERE {
    ?jd foaf:name "Johnny Depp"@en .
}
```

### Answer:

?jd
< <a href="http://dbpedia.org/resource/Johnny_Depp">http://dbpedia.org/resource/Johnny_Depp</a> >

# SPARQL Examples (ii)

## Films starring “Johnny Depp”

```
PREFIX foaf: <http://xmlns.com/foaf/0.1/>
PREFIX dbo: <http://dbpedia.org/ontology/>
SELECT ?m WHERE {
    ?jd foaf:name "Johnny Depp"@en .
    ?m dbo:starring ?jd .
}
```

(\*) `dbo:starring` comes from the <https://dbpedia.org/ontology/>

## SPARQL Examples (ii)

### Films starring “Johnny Depp”

```
PREFIX foaf: <http://xmlns.com/foaf/0.1/>
PREFIX dbo: <http://dbpedia.org/ontology/>
SELECT ?m WHERE {
    ?jd foaf:name "Johnny Depp"@en .
    ?m dbo:starring ?jd .
}
```

### Answer:

?m
<a href="http://dbpedia.org/resource/Dead_Man">&lt;http://dbpedia.org/resource/Dead_Man&gt;</a> <a href="http://dbpedia.org/resource/Edward_Scissorhands">&lt;http://dbpedia.org/resource/Edward_Scissorhands&gt;</a> <a href="http://dbpedia.org/resource/Arizona_Dream">&lt;http://dbpedia.org/resource/Arizona_Dream&gt;</a> ...

(\*) `dbo:starring` comes from the <https://dbpedia.org/ontology/>

## SPARQL Examples (iii)

### Names of people who co-starred with “Johnny Depp”

```
SELECT DISTINCT ?costar WHERE {  
    ?jd foaf:name "Johnny Depp"@en .  
    ?m dbo:starring ?jd .  
    ?m dbo:starring ?other .  
    ?other foaf:name ?costar .  
}
```



## SPARQL Examples (iii)

### Names of people who co-starred with “Johnny Depp”

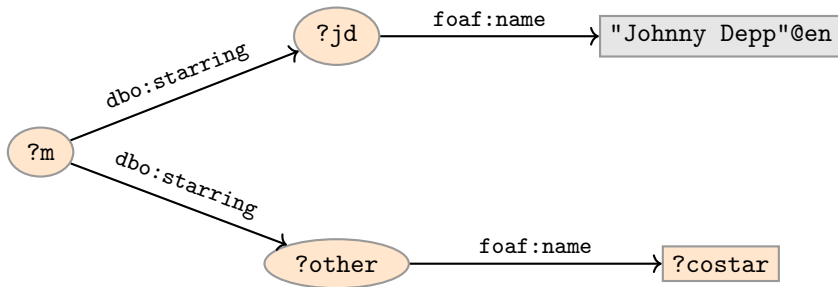
```
SELECT DISTINCT ?costar WHERE {  
    ?jd foaf:name "Johnny Depp"@en .  
    ?m dbo:starring ?jd .  
    ?m dbo:starring ?other .  
    ?other foaf:name ?costar .  
}
```

### Answer:

?costar
"Al Pacino"@en
"Antonio Banderas"@en
"Johnny Depp"@en
"Marlon Brando"@en
...

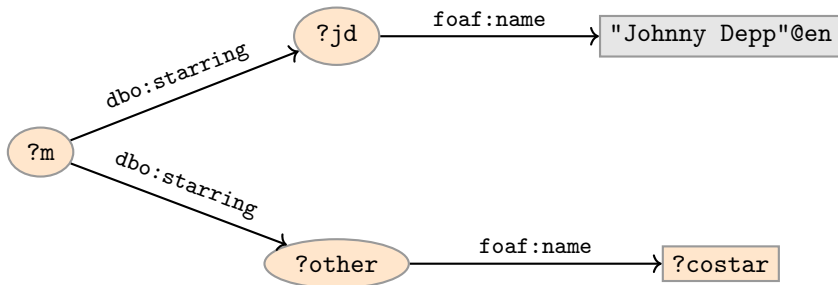
# Graph Patterns

The previous SPARQL query as a graph:



# Graph Patterns

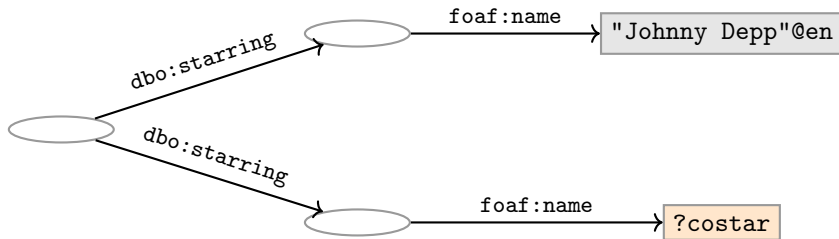
The previous SPARQL query as a graph:



**Pattern matching:** assign values to variables to make this a sub-graph of the RDF graph!

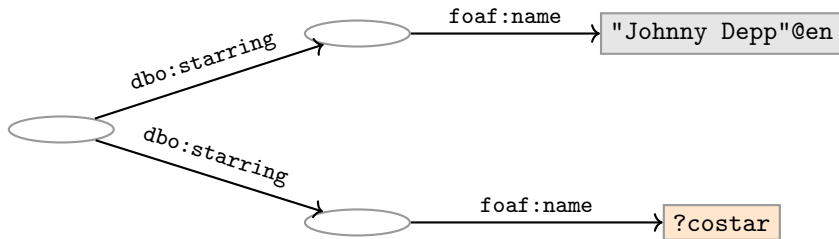
## Graph with blank nodes

Variables not SELECTed can equivalently be blank:



## Graph with blank nodes

Variables not SELECTed can equivalently be blank:



**Pattern matching:** a function that assigns values (*i.e.*, resource, a blank node, or a literal) to variables **and blank nodes** to make this a sub-graph of the RDF graph!

---

## SPARQL Systematically

# Components of a SPARQL query

```
PREFIX foaf: <http://xmlns.com/foaf/0.1/>
PREFIX dbo: <http://dbpedia.org/ontology/>
SELECT DISTINCT ?costar
WHERE {
    ?jd foaf:name "Johnny Depp"@en .
    ?m dbo:starring ?jd .
    ?m dbo:starring ?other .
    ?other foaf:name ?costar .
    FILTER (STR(?costar)!="Johnny Depp")
}
ORDER BY ?costar
LIMIT 10
```

# Components of a SPARQL query

## Prologue: prefix definitions

```
PREFIX foaf: <http://xmlns.com/foaf/0.1/>
PREFIX dbo: <http://dbpedia.org/ontology/>
SELECT DISTINCT ?costar
WHERE {
    ?jd foaf:name "Johnny Depp"@en .
    ?m dbo:starring ?jd .
    ?m dbo:starring ?other .
    ?other foaf:name ?costar .
    FILTER (STR(?costar)!="Johnny Depp")
}
ORDER BY ?costar
LIMIT 10
```



## Components of a SPARQL query

**Results:** (1) query type (SELECT, ASK, CONSTRUCT, DESCRIBE), (2) remove duplicates (DISTINCT, REDUCED), (3) variable list.

```
PREFIX foaf: <http://xmlns.com/foaf/0.1/>
```

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

```
SELECT DISTINCT ?costar
```

```
WHERE {
```

```
    ?jd foaf:name "Johnny Depp"@en .
```

```
    ?m dbo:starring ?jd .
```

```
    ?m dbo:starring ?other .
```

```
    ?other foaf:name ?costar .
```

```
    FILTER (STR(?costar)!="Johnny Depp")
```

```
}
```

```
ORDER BY ?costar
```

# Components of a SPARQL query

Query pattern: graph pattern to be matched

```
PREFIX foaf: <http://xmlns.com/foaf/0.1/>
PREFIX dbo: <http://dbpedia.org/ontology/>
SELECT DISTINCT ?costar
WHERE {
    ?jd foaf:name "Johnny Depp"@en .
    ?m dbo:starring ?jd .
    ?m dbo:starring ?other .
    ?other foaf:name ?costar .
    FILTER (STR(?costar)!="Johnny Depp")
}
ORDER BY ?costar
LIMIT 10
```

# Components of a SPARQL query

## Solution modifiers: ORDER BY, LIMIT, OFFSET

```
PREFIX foaf:  <http://xmlns.com/foaf/0.1/>
PREFIX dbo:  <http://dbpedia.org/ontology/>
SELECT DISTINCT ?costar
WHERE {
    ?jd foaf:name "Johnny Depp"@en .
    ?m dbo:starring ?jd .
    ?m dbo:starring ?other .
    ?other foaf:name ?costar .
    FILTER (STR(?costar)!="Johnny Depp")
}
```

ORDER BY ?costar

LIMIT 10

# Types of Queries (i)

SELECT Compute table of bindings for variables

```
SELECT DISTINCT ?a ?b WHERE {  
  [ dbo:starring ?a ;  
    dbo:starring ?b ]  
}
```

## Types of Queries (i)

**SELECT** Compute table of bindings for variables

```
SELECT DISTINCT ?a ?b WHERE {  
  [ dbo:starring ?a ;  
    dbo:starring ?b ]  
}
```

**CONSTRUCT** Use bindings to construct a new RDF graph

```
CONSTRUCT {  
  ?a foaf:knows ?b .  
} WHERE {  
  [ dbo:starring ?a ;  
    dbo:starring ?b ]  
}
```

## Types of Queries (ii)

ASK Answer (yes/no) whether there is  $\geq 1$  match

```
ASK WHERE {  
    ?jd foaf:name "Johnny Depp"@en .  
}
```

## Types of Queries (ii)

ASK Answer (yes/no) whether there is  $\geq 1$  match

```
ASK WHERE {  
    ?jd foaf:name "Johnny Depp"@en .  
}
```

DESCRIBE Returns an RDF graph with data about matching resources

```
DESCRIBE ?jd WHERE {  
    ?jd foaf:name "Johnny Depp"@en .  
}
```

---

## SPARQL Systematically: Solution Modifiers



## Solution Sequences and Modifiers

- Permitted to SELECT queries only
- SELECT treats solutions as a sequence (**solution sequence**)
- Query patterns generate an **unordered collection** of solutions
- **Sequence modifiers** can modify the solution sequence (not the solution itself). Applied in this order:
  - Order
  - Projection
  - Distinct
  - Reduced
  - Offset
  - Limit

# ORDER BY

- Used to sort the solution sequence in a given way:
- `SELECT ... WHERE ... ORDER BY ...`
- `ASC` for ascending order (default) and `DESC` for descending order

# ORDER BY

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- `SELECT ... WHERE ... ORDER BY ...`
- ASC for ascending order (default) and DESC for descending order
- E.g.

```
SELECT ?city ?pop WHERE {  
    ?city dbo:country ?country ;  
        dbo:populationUrban ?pop .  
} ORDER BY ?country DESC(?pop)
```

## ORDER BY

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- `SELECT ... WHERE ... ORDER BY ...`
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- E.g.  

```
SELECT ?city ?pop WHERE {  
    ?city dbo:country ?country ;  
        dbo:populationUrban ?pop .  
} ORDER BY ?country DESC(?pop)
```
- Standard defines **sorting conventions** for literals, URIs, etc.
- Not all “sorting” variables are required to appear in the SELECTION.

## ORDER BY (Example)

```
SELECT DISTINCT ?costar
WHERE {
    ?jd foaf:name "Johnny Depp"@en .
    ?m dbo:starring ?jd .
    ?m dbo:starring ?other .
    ?other foaf:name ?costar .
    FILTER (STR(?costar)!="Johnny Depp")
}
ORDER BY ?costar
```

## Projection, DISTINCT, REDUCED

- **Projection** (*i.e.*, SELECTed variables) means that only some variables are part of the solution
  - Done with `SELECT ?x ?y WHERE {?x dbo:starring ?y . }`

## Projection, DISTINCT, REDUCED

- **Projection** (*i.e.*, SELECTed variables) means that only some variables are part of the solution
  - Done with `SELECT ?x ?y WHERE {?x dbo:starring ?y . }`
- **DISTINCT eliminates (all) duplicate** solutions:
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  - A solution is a duplicate if it assigns the **same RDF terms to all variables** as another solution.

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  - A solution is a duplicate if it assigns the **same RDF terms to all variables** as another solution.
- **REDUCED** allows to **remove some** or all duplicate solutions
  - Done with `SELECT REDUCED ?x ?y WHERE {?x dbo:starring ?y . }`
  - Motivation: Can be expensive to find and remove all duplicates
  - Behaviour left to the SPARQL engine.



# OFFSET and LIMIT

- LIMIT: limits the number of results
- OFFSET: position/index of the first returned result
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- For example, solutions number 51 to 60:  

```
SELECT ?x ?y WHERE {?x dbo:starring ?y .} ORDER BY ?x  
LIMIT 10 OFFSET 50
```

## OFFSET and LIMIT

- LIMIT: limits the number of results
- OFFSET: position/index of the first returned result
- Useful for paging through a large set of solutions
- For example, solutions number 51 to 60:  

```
SELECT ?x ?y WHERE {?x dbo:starring ?y .} ORDER BY ?x  
LIMIT 10 OFFSET 50
```
- LIMIT and OFFSET can be used separately
- OFFSET not meaningful without ORDER BY.

## OFFSET and LIMIT (Example)

```
SELECT DISTINCT ?costar
WHERE {
    ?jd foaf:name "Johnny Depp"@en .
    ?m dbo:starring ?jd .
    ?m dbo:starring ?other .
    ?other foaf:name ?costar .
    FILTER (STR(?costar)!="Johnny Depp")
}
ORDER BY ?costar
LIMIT 10 OFFSET 50
```

---

## SPARQL Systematically: Query Graph Patterns

# Query patterns

- Types of graph patterns for the query pattern (**WHERE clause**):
  - ✓ Basic Graph Patterns (BGP)
  - Filters or Constraints (FILTER)
  - Optional Graph Patterns (OPTIONAL)
  - Union Graph Patterns (UNION, Matching Alternatives)
  - Graph Graph Patterns (RDF Datasets)

## Filters (i)

- A set of triple patterns may include **constraints** or **filters**
- Reduces matches of surrounding group where filter applies
- Example:

```
SELECT ?x
WHERE {
    ?x a dbo:Place ;
        dbo:populationUrban ?pop .
    FILTER (?pop > 1000000)
}
```

## Filters (ii)

### – Example:

```
SELECT DISTINCT ?costar
FROM <http://dbpedia_dataset>
WHERE {
    ?jd foaf:name "Johnny Depp"@en .
    ?m dbo:starring ?jd .
    ?m dbo:starring ?other .
    ?other foaf:name ?costar .
    FILTER (STR(?costar)!="Johnny Depp")
}
ORDER BY ?costar
LIMIT 10 OFFSET 50
```



## Filters: Functions and Operators

- Usual binary operators: `||`, `&&`, `=`, `!=`, `<`, `>`, `<=`, `>=`, `+`, `-`, `*`, `/`.
- Usual unary operators: `!`, `+`, `-`.
- Unary tests: `bound(?var)`, `isURI(?var)`, `isBlank(?var)`, `isLiteral(?var)`.
- Accessors: `str(?var)`, `lang(?var)`, `datatype(?var)`, `year(?date)`, `xsd:integer(?value)`
- `regex` is used to match a variable with a regular expression. *Always use with* `str(?var)`. E.g.: `regex(str(?costar), "Alpacino")`.

**More details in specification:** <http://www.w3.org/TR/rdf-sparql-query/>

## OPTIONAL Patterns

- Allows a match to leave some variables **unbound** (e.g. no data is available). *e.g.*,:

```
WHERE {  
    ?x a dbo:Person ;  
        foaf:name ?name .  
    OPTIONAL {  
        ?x dbo:birthDate ?date .  
    }  
}
```

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        foaf:name ?name .  
    OPTIONAL {  
        ?x dbo:birthDate ?date .  
    }  
}
```

- ?x and ?name bound in every match, ?date is **bound if available**.
- Groups can contain several **optional parts**, evaluated separately

## OPTIONAL Patterns: with FILTER

- Example:

```
WHERE {  
  ?x a dbo:Person ;  
    foaf:name ?name .  
  OPTIONAL {  
    ?x dbo:birthDate ?date .  
    FILTER (?date > "1980-01-01T00:00:00"^^xsd:dateTime)  
  }  
}
```

- ?x and ?name bound in every match, ?date is **bound if available** and **from 1980 onwards**.

## Matching Alternatives (UNION)

- A UNION pattern matches if any of some alternatives matches
- E.g.

```
SELECT DISTINCT ?writer
WHERE{
    ?s rdf:type dbo:Book .
    {
        ?s dbo:author ?writer .
    }
    UNION
    {
        ?s dbo:writer ?writer .
    }
}
```

## 'Graph' Graph Patterns (RDF datasets)

- SPARQL queries are executed against an **RDF dataset**
- An RDF dataset comprises
  - One **default graph** (unnamed) graph. [Target for this course.](#)
  - Zero or more **named graphs** identified by an URI

## 'Graph' Graph Patterns (RDF datasets)

- SPARQL queries are executed against an **RDF dataset**
- An RDF dataset comprises
  - One **default graph** (unnamed) graph. [Target for this course.](#)
  - Zero or more **named graphs** identified by an URI
- FROM and FROM NAMED keywords allows to select an RDF dataset
- Keyword GRAPH makes the named graphs the **active graph** for pattern matching



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## SPARQL 1.1

## SPARQL 1.1: new features

- The new features in **SPARQL 1.1 QUERY** language:
  - Assignments and Expressions
  - Aggregates
  - Subqueries
  - Negation (new syntax)
  - Property paths

## SPARQL 1.1: new features

- The new features in **SPARQL 1.1 QUERY language**:
  - Assignments and Expressions
  - Aggregates
  - Subqueries
  - Negation (new syntax)
  - Property paths
- Specification for:
  - **SPARQL 1.1 UPDATE Language**
  - **SPARQL 1.1 Federated Queries**
  - **SPARQL 1.1 Entailment Regimes**

# Assignment and Expressions

- The value of an expression can be assigned/bound to a new variable
- Can be used in SELECT, BIND or GROUP BY clauses:  
*(expression AS ?var)*

## Expressions in SELECT clause

```
SELECT ?city (xsd:integer(?pop)/xsd:float(?area) AS ?density)
{
  ?city dbo:populationTotal ?pop .
  ?city dbo:PopulatedPlace/areaTotal ?area .
  ?city dbo:country dbr:United_Kingdom .
  FILTER (xsd:float(?area)>0.0)
}
```

## Aggregates: Grouping and Filtering

- Solutions can optionally be grouped according to one or more expressions.
- To specify the group, use `GROUP BY`.
- If `GROUP BY` is not used, then **only one (implicit) group**

# Aggregates: Grouping and Filtering

- Solutions can optionally be grouped according to one or more expressions.
- To specify the group, use `GROUP BY`.
- If `GROUP BY` is not used, then **only one (implicit) group**
- To filter solutions resulting from grouping, use `HAVING`.
- `HAVING` operates over grouped solution sets, in the same way that `FILTER` operates over un-grouped ones.

# Aggregates: Example

## Actors with more than 15 movies

```
SELECT ?name (COUNT(?movie) AS ?mcount)
WHERE {
    ?actor foaf:name ?name .
    ?movie dbo:starring ?actor .
}
GROUP BY ?name
HAVING (COUNT(?movie) > 15)
ORDER BY DESC (?mcount)
```

# Aggregates: Example

## Actors with more than 15 movies

```
SELECT ?name (COUNT(?movie) AS ?mcount)
WHERE {
    ?actor foaf:name ?name .
    ?movie dbo:starring ?actor .
}
GROUP BY ?name
HAVING (COUNT(?movie) > 15)
ORDER BY DESC (?mcount)
```

† Only expressions consisting of aggregates and constants may be projected, together with variables in GROUP BY.



## Aggregates: common functions

- `Count` counts the number of times a variable has been bound.
- `Sum` sums numerical values of bound variables.
- `Avg` finds the average of numerical values of bound variables.
- `Min` finds the minimum of the numerical values of bound variables.
- `Max` finds the maximum of the numerical values of bound variables.

† Aggregates assume CWA and UNA

# Subqueries

- A way to embed SPARQL queries within other queries
- Subqueries are evaluated first and the results are projected to the outer query.

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- Subqueries are evaluated first and the results are projected to the outer query.

```
SELECT ?country ?pop (round(?pop/?worldpop*1000)/10 AS ?percentage) WHERE {  
  ?country rdf:type dbo:Country .  
  ?country dbo:populationTotal ?pop .  
  {  
    SELECT (sum(?p) AS ?worldpop) WHERE {  
      ?c rdf:type dbo:Country .  
      ?c dbo:populationTotal ?p .}  
  }  
} ORDER BY desc(?pop)
```

# Subqueries

- A way to embed SPARQL queries within other queries
- Subqueries are evaluated first and the results are projected to the outer query.

```
SELECT ?country ?pop (round(?pop/?worldpop*1000)/10 AS ?percentage) WHERE {  
  ?country rdf:type dbo:Country .  
  ?country dbo:populationTotal ?pop .  
  {  
    SELECT (sum(?p) AS ?worldpop) WHERE {  
      ?c rdf:type dbo:Country .  
      ?c dbo:populationTotal ?p .}  
  }  
} ORDER BY desc(?pop)
```

† Note that the *Sum()* aggregation is done over all the elements (single default group).

# Negation in SPARQL 1.1: MINUS and FILTER NOT EXISTS

Two ways to do negation. *e.g.*, retrieve people without a name:

```
SELECT DISTINCT * WHERE {  
    ?person a foaf:Person .  
    MINUS { ?person foaf:name ?name }  
}
```

```
SELECT DISTINCT * WHERE {  
    ?person a foaf:Person .  
    FILTER NOT EXISTS { ?person foaf:name ?name }  
}
```

## Property paths: basic motivation

- Some queries get needlessly large.
- SPARQL 1.1 define a small language to defined paths.
- Examples:
  - `city:ernesto foaf:knows+ ?friend` to extract all friends of friends.
  - `foaf:maker|dc:creator` instead of UNION.
  - Friend's names, `{ _:me foaf:knows/foaf:name ?friendsname }`.
  - Sum several items:  
`SELECT (sum(?cost) AS ?total) { :order :hasItem/:price ?cost }`

# Property paths: example

```
PREFIX foaf: <http://xmlns.com/foaf/0.1/>
PREFIX dbo: <http://dbpedia.org/ontology/>
SELECT DISTINCT ?costar
WHERE {
    ?m dbo:starring/foaf:name "Johnny Depp"@en .
    ?m dbo:starring/foaf:name ?costar .
    FILTER (STR(?costar)!="Johnny Depp")
}
ORDER BY ?costar
```

†Similar to blank node syntax.

# Property paths: syntax

Syntax Form	Matches
<code>iri</code>	An (property) IRI. A path of length one.
<code>^elt</code>	Inverse path (object to subject).
<code>elt1 / elt2</code>	A sequence path of <code>elt1</code> followed by <code>elt2</code> .
<code>elt1   elt2</code>	A alternative path of <code>elt1</code> or <code>elt2</code> (all possibilities are tried).
<code>elt*</code>	Seq. of zero or more matches of <code>elt</code> .
<code>elt+</code>	Seq. of one or more matches of <code>elt</code> .
<code>elt?</code>	Zero or one matches of <code>elt</code> .
<code>!iri</code> or <code>!(iri<sub>1</sub>   ...   iri<sub>n</sub>)</code>	Negated property set.
<code>!^iri</code> or <code>!(^iri<sub>1</sub>   ...   ^iri<sub>n</sub>)</code>	Negation of inverse path.
<code>!(iri<sub>1</sub>   ...   iri<sub>j</sub>   ^iri<sub>j+1</sub>   ...   ^iri<sub>n</sub>)</code>	Negated combination of forward and inverse properties.
<code>(elt)</code>	A group path <code>elt</code> , brackets control precedence.

\* `elt` is a path element, which may itself be composed of path constructs (see Syntax form).



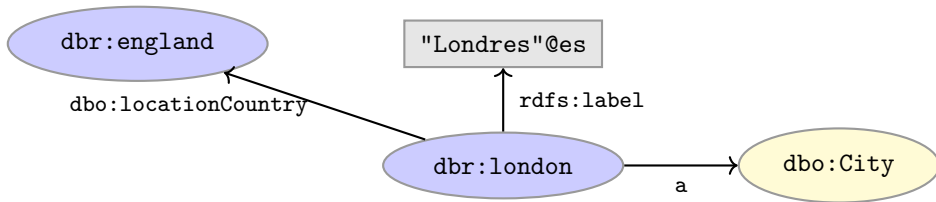
---

## SPARQL Summary

# SPARQL Summary (i)

## Return all Cities:

```
PREFIX dbo: <http://dbpedia.org/ontology/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
SELECT DISTINCT ?city WHERE {
    ?city rdf:type dbo:City .
}
```



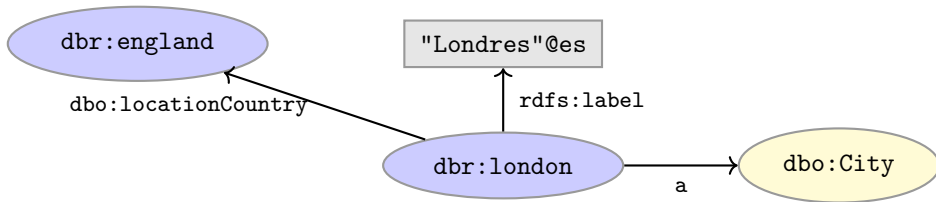
# SPARQL Summary (i)

**Return all Cities:** **Query Result= {dbr:london}**

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

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
```

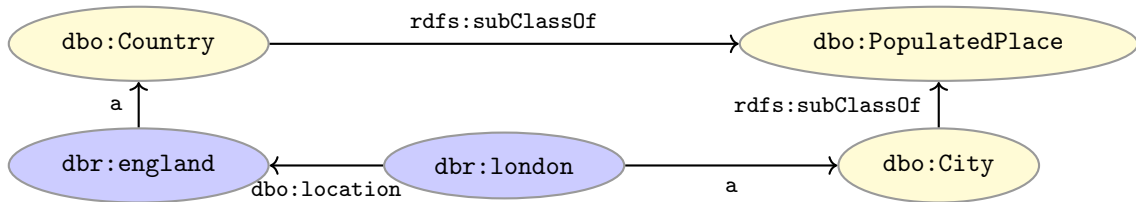
```
SELECT DISTINCT ?city WHERE {  
    ?city rdf:type dbo:City .  
}
```



## SPARQL Summary (ii)

### Return all Populated Places:

```
PREFIX dbo: <http://dbpedia.org/ontology/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
SELECT DISTINCT ?place WHERE {
    ?place rdf:type dbo:PopulatedPlace .
}
```



## SPARQL Summary (ii)

**Return all Populated Places: Query Result= {}**

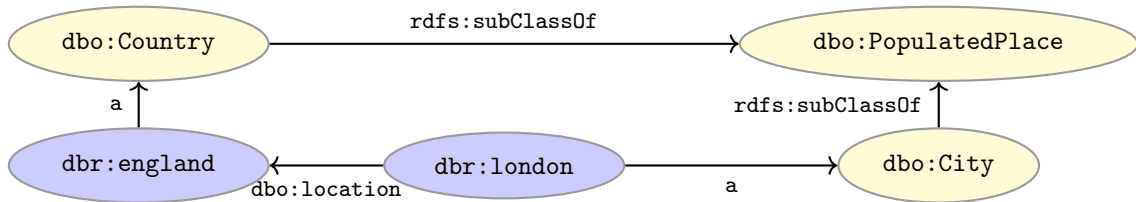
```
PREFIX dbo: <http://dbpedia.org/ontology/>
```

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
```

```
SELECT DISTINCT ?place WHERE {
```

```
    ?place rdf:type dbo:PopulatedPlace .
```

```
}
```

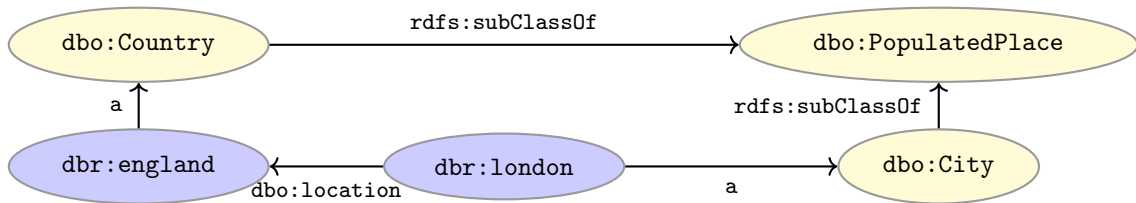


---

## PART II: Reasoning with Knowledge Graphs

# Implicit Knowledge in KGs: Entailment

- Given a set of triples  $\mathcal{G}$  (*i.e.*, a Graph), can we entail a triple  $t$  ( $\mathcal{G} \models t$ )?
- Can we entail the triple: `dbr:london rdf:type dbo:PopulatedPlace` and add it to the graph below? (*Graph expansion via reasoning*).
- Similarly for `dbr:england`



## Model-Theoretic Semantics (i)

- **Interpretations** might be conceived as potential "realities" or "worlds".
- Interpretations assign values to elements.
  - (*The **intuitions** behind set-theory are **formally represented**.*)



## Model-Theoretic Semantics (i)

- **Interpretations** might be conceived as potential "realities" or "worlds".
- Interpretations assign values to elements.
  - (*The **intuitions** behind set-theory are **formally represented**.*)
- Given an interpretation  $\mathcal{I}$  and a set of triples  $\mathcal{G}$
- $\mathcal{G}$  is valid in  $\mathcal{I}$  (written  $\mathcal{I} \models \mathcal{G}$ ), iff  $\mathcal{I} \models t$  for all  $t \in \mathcal{G}$ .
- Then  $\mathcal{I}$  is also called a **model** of  $\mathcal{G}$ .

## Model-Theoretic Semantics (ii)

- The following interpretation  $\mathcal{I}$  is a model of our example  $\mathcal{G}$ :
  - $\text{dbo:City}^{\mathcal{I}} = \{\text{dbr:london}\}$
  - $\text{dbo:Country}^{\mathcal{I}} = \{\text{dbr:england}\}$
  - $\text{dbo:PopulatedPlace}^{\mathcal{I}} = \{\text{dbr:london}, \text{dbr:england}\}$
  - $\text{dbo:location}^{\mathcal{I}} = \{\langle \text{dbr:london}, \text{dbr:england} \rangle\}$

## Model-Theoretic Semantics (ii)

- The following interpretation  $\mathcal{I}$  is a model of our example  $\mathcal{G}$ :
  - $\text{dbo:City}^{\mathcal{I}} = \{\text{dbr:london}\}$
  - $\text{dbo:Country}^{\mathcal{I}} = \{\text{dbr:england}\}$
  - $\text{dbo:PopulatedPlace}^{\mathcal{I}} = \{\text{dbr:london}, \text{dbr:england}\}$
  - $\text{dbo:location}^{\mathcal{I}} = \{\langle \text{dbr:london}, \text{dbr:england} \rangle\}$
- $\mathcal{I} \models \mathcal{G}$  (is a model of  $\mathcal{G}$ ) as the following holds:
  - $\text{dbo:City}^{\mathcal{I}} \subseteq \text{dbo:PopulatedPlace}^{\mathcal{I}}$
  - $\text{dbo:Country}^{\mathcal{I}} \subseteq \text{dbo:PopulatedPlace}^{\mathcal{I}}$
  - $\text{dbr:london}^{\mathcal{I}} \in \text{dbo:City}^{\mathcal{I}}$

## Model-Theoretic Semantics (iii)

- $t = \text{dbr:london} \text{ rdf:type } \text{dbo:PopulatedPlace}$
- Does  $\mathcal{I} \models t$  ?

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- $t = \text{dbr:london} \text{ rdf:type } \text{dbo:PopulatedPlace}$
- Does  $\mathcal{I} \models t$  ?
  - **Yes:**  $\text{dbo:PopulatedPlace}^{\mathcal{I}} = \{\text{dbr:london}, \text{dbr:england}\}$
- Does  $\mathcal{G} \models t$  ?

## Model-Theoretic Semantics (iii)

- $t = \text{dbr:london rdf:type dbo:PopulatedPlace}$
- Does  $\mathcal{I} \models t$  ?
  - **Yes:**  $\text{dbo:PopulatedPlace}^{\mathcal{I}} = \{\text{dbr:london}, \text{dbr:england}\}$
- Does  $\mathcal{G} \models t$  ?
  - **if and only if**
    - For **any interpretation**  $\mathcal{I}$  with  $\mathcal{I} \models \mathcal{G}$
    - $\mathcal{I} \models t$ .
  - (Yes, in this case too.)

## Model-Theoretic Semantics (iii)

- $t = \text{dbr:london rdf:type dbo:PopulatedPlace}$
- Does  $\mathcal{I} \models t$  ?
  - **Yes:**  $\text{dbo:PopulatedPlace}^{\mathcal{I}} = \{\text{dbr:london}, \text{dbr:england}\}$
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    - $\mathcal{I} \models t$ .
  - (Yes, in this case too.)
- Does  $\mathcal{G} \models t_2$  ( $t_2 = \text{dbr:london rdf:type dbo:Country}$ )?



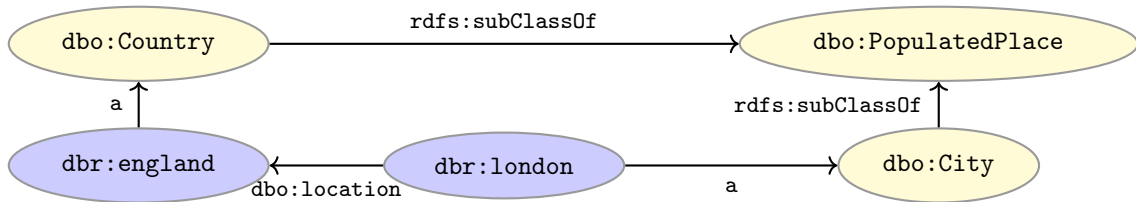
## Model-Theoretic Semantics (iii)

- $t = \text{dbr:london rdf:type dbo:PopulatedPlace}$
- Does  $\mathcal{I} \models t$  ?
  - **Yes:**  $\text{dbo:PopulatedPlace}^{\mathcal{I}} = \{\text{dbr:london}, \text{dbr:england}\}$
- Does  $\mathcal{G} \models t$  ?
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    - For **any interpretation**  $\mathcal{I}$  with  $\mathcal{I} \models \mathcal{G}$
    - $\mathcal{I} \models t$ .
  - (Yes, in this case too.)
- Does  $\mathcal{G} \models t_2$  ( $t_2 = \text{dbr:london rdf:type dbo:Country}$ )?
  - **No:** Our  $\mathcal{I}$  is a counter example.  $\mathcal{I} \models \mathcal{G}$  but  $\mathcal{I} \not\models t_2$

# SPARQL Example: with entailment

## Return all Populated places:

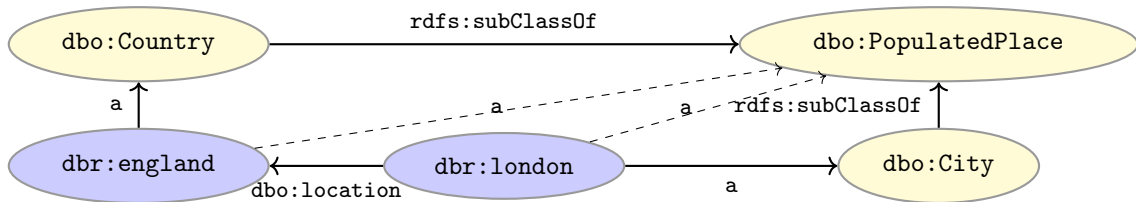
```
PREFIX dbo: <http://dbpedia.org/ontology/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
SELECT DISTINCT ?place WHERE {
    ?place rdf:type dbo:PopulatedPlace .
}
```



# SPARQL Example: with entailment

Return all Populated places: **Query Result= {dbr:england, dbr:london}**

```
PREFIX dbo: <http://dbpedia.org/ontology/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
SELECT DISTINCT ?place WHERE {
    ?place rdf:type dbo:PopulatedPlace .
}
```



# Model-Theoretic Semantics in practice

- Model-theoretic semantics yields an unambiguous notion of entailment.
- In principle, **all interpretations** need to be considered.
- However there are **infinitely many** such interpretations,
- An **algorithm should terminate** in finite time.

**Foundations of Semantic Web Technologies.** Chapter 3.

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## Syntactic methods for Entailment

# Syntactic Reasoning

- From the computation point of view, we need means to decide **entailment syntactically**.
- Syntactic methods operate
  - only on the form of a statement, that is on its **concrete grammatical structure** (*i.e.*, triples),
  - without recurring to interpretations.
- Syntactic methods should justify that their so-called **operational semantics** are expected with respect to model-theoretic semantics.

## OWL 2 Reasoning Algorithms (i)

- Reasoning in OWL 2 is typically based on **(Hyper)Tableau Reasoning Algorithms** (tableau = truth tree)
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- Algorithm tries to construct an **abstraction** of a model.
- State-of-the-art algorithms:
  - *e.g.*, **HermiT** (default option in Protégé).



## OWL 2 Reasoning Algorithms (ii)

- ✓ OWL 2 Reasoners are optimised for TBox tasks.
- ✓ Effective with many realistic ontologies.
- ✗ ABox reasoning tasks are untractable with relatively small KGs.
- ✗ Decidability is open when querying OWL-based KGs with SPARQL.
  - There are some tricks to make it work, but complexity is still high.
- ✗ The main problem is that one cannot just expand the (knowledge) graph and then execute a SPARQL query
- ✓ Solution: **OWL 2 Profiles**

Computational properties: [https://www.w3.org/TR/owl2-profiles/#Computational\\_Properties](https://www.w3.org/TR/owl2-profiles/#Computational_Properties)

Seminars by Prof. Ian Horrocks: <http://www.cs.ox.ac.uk/people/ian.horrocks/Seminars/seminars.html>

# OWL 1, OWL 2 (profiles) and RDFS

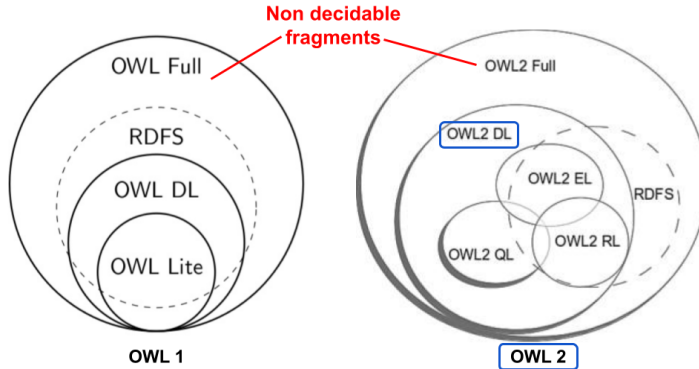
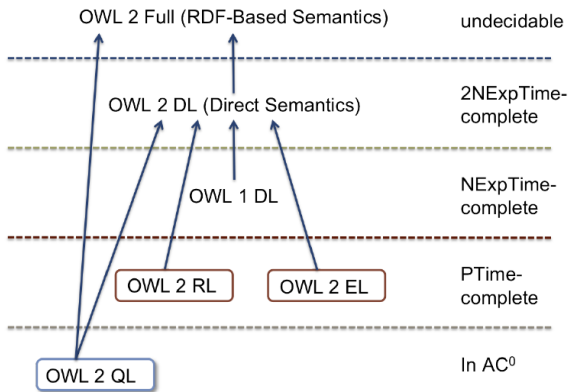


Image adapted from Olivier Cure and Guillaume Blin. RDF Database Systems (Chapter 3). 2015. Elsevier.

# Data Complexity in OWL 2 and Profiles



<https://www.w3.org/TR/owl2-profiles/>

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## OWL 2 Profiles summary

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  - **OWL 2 QL:**
    - Specifically designed for efficient database integration.
  - **OWL 2 EL:**
    - A lightweight language with polynomial time reasoning.
  - **OWL 2 RL:**
    - Designed for compatibility with rule-based inference tools.
    - **Efficient reasoning with large datasets.**



## OWL QL Profile

- ✓ Required language so that queries can be rewritten using the TBox.
- ✓ Used in Ontology Based Data Access (OBDA) where SPARQL queries are translated to SQL

Not supported, simplified:

- ✗ disjunction
- ✗ universal quantification, cardinalities, and functional roles
- ✗ `= (SameIndividual)`
- ✗ enumerations (closed classes)
- ✗ subproperties of chains, transitivity
- ✗ reduced list of datatypes

## OWL EL Profile

- ✓ Standard reasoning tasks in P time
- ✓ Very good for large ontologies.
- ✓ Used in many biomedical ontologies (*e.g.*, SNOMED CT).
- ✓ Reasoning can be performed via saturation (*i.e.*, **inference rules**).

Not supported features, simplified:

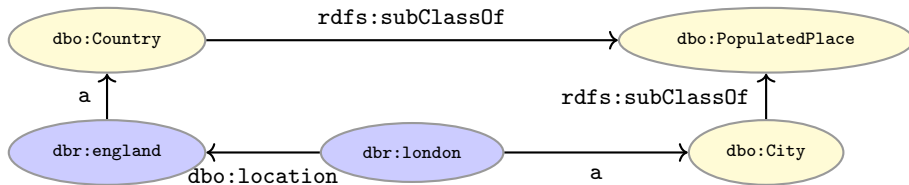
- ✗ negation (but  $C \sqcap D \sqsubseteq \perp$  possible)
- ✗ disjunction
- ✗ universal quantification and cardinalities
- ✗ inverse roles and some role characteristics
- ✗ reduced list of datatypes

## OWL 2 RL Profile

- ✗ Puts syntactic constraints in the way in which constructs are used (i.e., syntactic subset of OWL 2).
- ✗ Imposes a reduced list of allowed datatypes.
- ✓ OWL 2 RL axioms can be directly translated into **datalog rules**.
- ✓ Enables desirable computational properties using **rule-based** reasoning engines.

# Reasoning in the OWL QL Profile

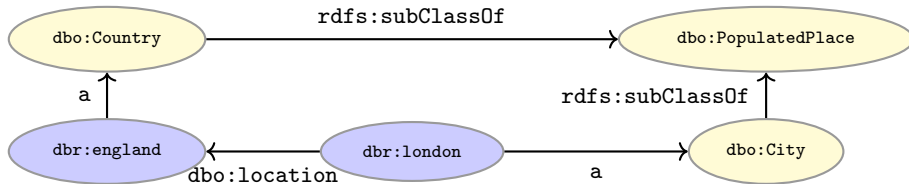
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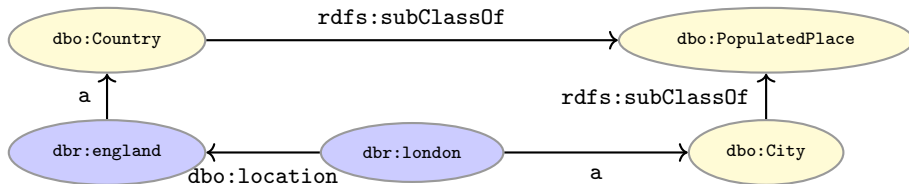


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$Q$ : `SELECT DISTINCT ?place WHERE {?place rdf:type dbo:PopulatedPlace . }`

$Q'$ : `SELECT DISTINCT ?place WHERE {  
 {?place rdf:type dbo:PopulatedPlace .}  
 UNION {?place rdf:type dbo:Country .}  
 UNION {?place rdf:type dbo:City .} }`



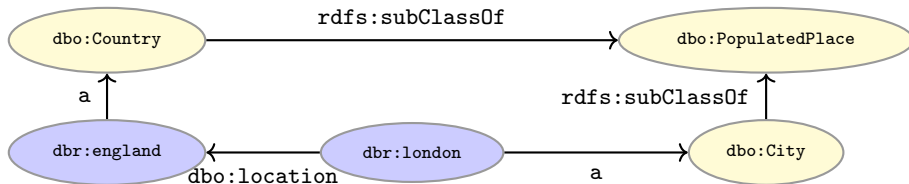
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 {?place rdf:type dbo:PopulatedPlace .}  
 UNION {?place rdf:type dbo:Country .}  
 UNION {?place rdf:type dbo:City .} }`

$Q'$  Result= {dbr:england, dbr:london}



---

## Inference rules



## Inference rules (i)

- Inference rules (also known as deduction rules or derivation rules) is an option to **describe syntactic solutions**.
- The general form of an inference rule is:

$$\frac{P_1, \dots, P_n}{P}$$

- the  $P_i$  are **premises** (body)
  - and  $P$  is the **conclusion** (head).
- An inference rule may have,
  - any number of premises (typically one or two),
  - but only one conclusion.

## Inference rules (ii)

- Recall that syllogisms (*i.e.*, inference) can be traced back to Aristotle
- Example:

All human are mortal  
Socrates is a human  
-----  
Therefore, Socrates is mortal

## Inference rules (iii)

- The whole set of inference rules given for a logic is called **deduction calculus**.
- $\vdash$  is the **inference relation**, while  $\models$  was the entailment relation using model theoretic semantics.
  - We write  $\Gamma \vdash P$  if we can deduce  $P$  from the premises  $\Gamma$ .

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  - We write  $\Gamma \vdash P$  if we can deduce  $P$  from the premises  $\Gamma$ .
- **In our example:**
  - the **premises**  $\Gamma$  are a **set of triples** (*i.e.*, a (sub)graph  $\mathcal{G}$ ),
  - the **conclusion**  $P$  is a **new triple**  $t$
  - After applying the rules to  $\mathcal{G}$  we will get an **expanded graph**  $\mathcal{G}'$

# RDFS Inference Rules

RDFS supports several rules. Organized into three groups:

## 1. **Type propagation:**

- “London is a City, all Cities are populated places, so...”

## 2. **Property propagation:**

- “London is the capital of England, anything that is capital of a country is also located in that country, so...”

## 3. **Domain and range propagation:**

- “Everything that has a capital is a country, so England is a...”
- “Everything that is a capital is a city, so London is a...”

RDFS Entailment Rules: <https://www.w3.org/TR/rdf-mt/#RDFSRules>

# Type propagation

- **Members of superclasses:**

$$\frac{A \text{ rdfs:subClassOf } B . \quad x \text{ rdf:type } A .}{x \text{ rdf:type } B .} \text{ rdfs9}$$

(\*) rdfs9, rdfs10, rdfs11 are the names of the inference rules in the W3C standard.  
A, B are classes; x is an instance.

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- **Reflexivity of sub-class relation:**

$$\frac{A \text{ rdf:type rdfs:Class } .}{A \text{ rdfs:subClassOf } A .} \text{ rdfs10}$$

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- **Transitivity of sub-class relation:**

$$\frac{A \text{ rdfs:subClassOf } B . \quad B \text{ rdfs:subClassOf } C .}{A \text{ rdfs:subClassOf } C .} \text{ rdfs11}$$

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A, B are classes; x is an instance.



# Type propagation: Examples

- **Members of superclasses:**

$$\frac{\text{:City rdfs:subClassOf :PopulatedPlace .} \quad \text{:london rdf:type :City .}}{\text{:london rdf:type :PopulatedPlace .}} \text{ rdfs9}$$

- **Reflexivity of sub-class relation:**

$$\frac{\text{:City rdf:type rdfs:Class .}}{\text{:City rdfs:subClassOf :City .}} \text{ rdfs10}$$

- **Transitivity of sub-class relation:**

$$\frac{\text{:City rdfs:subClassOf :PopulatedPlace .} \quad \text{:PopulatedPlace rdfs:subClassOf :Place .}}{\text{:City rdfs:subClassOf :Place .}} \text{ rdfs11}$$

# Property Propagation

## – Transitivity:

$$\frac{P \text{ rdfs:subPropertyOf } Q . \quad Q \text{ rdfs:subPropertyOf } R .}{P \text{ rdfs:subPropertyOf } R .} \text{ rdfs5}$$

(\*) P, Q are properties; u, v are instances.

# Property Propagation

- **Transitivity:**

$$\frac{P \text{ rdfs:subPropertyOf } Q . \quad Q \text{ rdfs:subPropertyOf } R .}{P \text{ rdfs:subPropertyOf } R .} \text{ rdfs5}$$

- **Reflexivity:**

$$\frac{P \text{ rdf:type } \text{rdf:Property} .}{P \text{ rdfs:subPropertyOf } P .} \text{ rdfs6}$$

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# Property Propagation

- **Transitivity:**

$$\frac{P \text{ rdfs:subPropertyOf } Q . \quad Q \text{ rdfs:subPropertyOf } R .}{P \text{ rdfs:subPropertyOf } R .} \text{ rdfs5}$$

- **Reflexivity:**

$$\frac{P \text{ rdf:type } \text{rdf:Property} .}{P \text{ rdfs:subPropertyOf } P .} \text{ rdfs6}$$

- **Property transfer:**

$$\frac{P \text{ rdfs:subPropertyOf } Q . \quad u P v .}{u Q v .} \text{ rdfs7}$$

(\*) P, Q are properties; u, v are instances.

# Property Propagation: Examples

## – Transitivity:

$$\frac{\text{ :has\_writer rdfs:subPropertyOf :has\_author . } \quad \text{ :has\_author rdfs:subPropertyOf :has\_creator . }}{\text{ :has\_writer rdfs:subPropertyOf :has\_creator . }} \text{ rdfs5}$$

## – Reflexivity:

$$\frac{\text{ :has\_writer rdf:type rdf:Property . }}{\text{ :has\_writer rdfs:subPropertyOf :has\_writer . }} \text{ rdfs6}$$

## – Property transfer:

$$\frac{\text{ :has\_author rdfs:subPropertyOf :has\_creator . } \quad \text{ :Hamlet :has\_author :Shakespeare . }}{\text{ :Hamlet :has\_creator :Shakespeare . }} \text{ rdfs7}$$

# Domain and range propagation

Typing triggered by the use of properties.

– **Domain propagation:**

$$\frac{P \text{ rdfs:domain } A . \quad x P y .}{x \text{ rdf:type } A .} \text{ rdfs2}$$

(\*) P, Q are properties; x, y are instances.

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- **Domain propagation:**

$$\frac{P \text{ rdfs:domain } A . \quad x P y .}{x \text{ rdf:type } A .} \text{ rdfs2}$$

- **Range propagation:**

$$\frac{P \text{ rdfs:range } B . \quad x P y .}{y \text{ rdf:type } B .} \text{ rdfs3}$$

(\*) P, Q are properties; x, y are instances.

# Domain and Range Propagation: Examples

## – Domain propagation:

$$\frac{\text{:capitalOf rdfs:domain :City .} \quad \text{:london :capitalOf :england .}}{\text{:london rdf:type :City .}} \text{ rdfs2}$$

## – Range propagation:

$$\frac{\text{:capitalOf rdfs:range :Country .} \quad \text{:london :capitalOf :england .}}{\text{:england rdf:type :Country .}} \text{ rdfs3}$$



## RDFS inference rules in our example

```

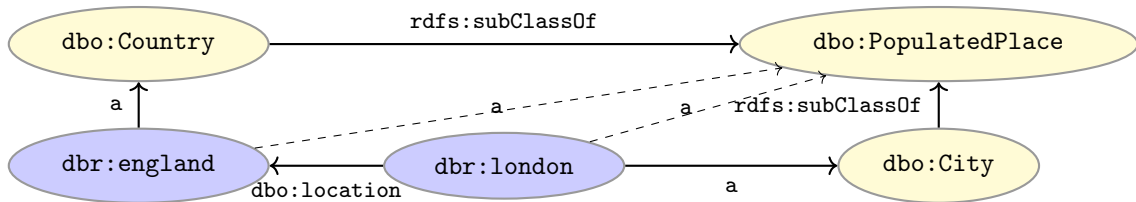
dbo:City rdfs:subClassOf dbo:PopulatedPlace .      dbr:london rdf:type dbo:City .
----- rdfs9
          dbr:london rdf:type dbo:PopulatedPace .

```

```

dbo:Country rdfs:subClassOf dbo:PopulatedPlace .      dbr:england rdf:type dbo:Country .
----- rdfs
              dbr:england rdf:type dbo:PopulatedPlace .

```



## Inference rules in the OWL EL Profile

- Reasoning can be performed via saturation<sup>†</sup> (*i.e.*, inference rules).
- For example:

$$\frac{A \sqsubseteq B \quad B \sqsubseteq C}{A \sqsubseteq C}$$
$$\frac{A \sqsubseteq \exists R.B \quad \exists S.B \sqsubseteq C \quad S \sqsubseteq R}{A \sqsubseteq C}$$

<sup>†</sup> Using a saturation-based approach over an OWL 2 ontology is not possible.

**ELK reasoner** (also available as Protégé plugin): <https://github.com/liveontologies/elk-reasoner/wiki>

## Inference rules in the OWL 2 RL Profile

- Reasoning via full materialisation of the graph, similarly to RDFS inference rules. *e.g.*:

$$\frac{p1 \text{ owl:inverseOf } p2 . \quad ?x ?p1 ?y .}{?y ?p2 ?x .}$$

- See W3C specification for further inference rules in OWL 2 RL in addition to the RDFS ones.

W3C: [https://www.w3.org/TR/owl2-profiles/#Reasoning\\_in\\_OWL\\_2\\_RL\\_and\\_RDF\\_Graphs\\_using\\_Rules](https://www.w3.org/TR/owl2-profiles/#Reasoning_in_OWL_2_RL_and_RDF_Graphs_using_Rules)

GraphDB: <https://graphdb.ontotext.com/documentation/standard/reasoning.html>

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## OWL 2 Important Practical Examples

# Open World Assumptions

## Closed World Assumption (**CWA**)

- Complete knowledge.
- Any statement that is not known to be true is false. (\*)
- Typical semantics for **database systems**.

# Open World Assumptions

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- Complete knowledge.
- Any statement that is not known to be true is false. (\*)
- Typical semantics for **database systems**.

## Open World Assumption (**OWA**)

- Potential incomplete knowledge.
- (\*) does not hold.
- Typical semantics for **logic-based systems** (including OWL).

# Name Assumptions

## Unique Name Assumption (**UNA**)

- Different names **always** denote different things.
  - E.g.,  $a^{\mathcal{I}} \neq b^{\mathcal{I}}$ .
- common in relational databases.

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  - $\text{dbpedia:Person}^{\mathcal{I}} = \text{foaf:Person}^{\mathcal{I}}$ .
  - $\text{wikidata:ernesto}^{\mathcal{I}} = \text{city:ernesto}^{\mathcal{I}}$



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Equal names (e.g., URIs) always denote the same “thing”.

- E.g., cannot have  $\text{city:ernesto}^{\mathcal{I}} \neq \text{city:ernesto}^{\mathcal{I}}$ .

# Necessary conditions and primitive classes

Hawaiian pizza **implies** having pineapple as ingredient (among others); but not the other way round.

Description: Hawaiian pizza

Equivalent To

SubClass Of

'American pizza'

?

@

×

○

hasIngredient some 'Tomato sauce'

?

@

×

○

hasIngredient some Cheese

?

@

×

○

hasIngredient some Ham

?

@

×

○

hasIngredient some Pineapple

?

@

×

○

NamedPizza

?

@

×

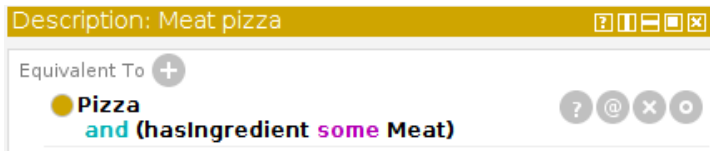
○

## Sufficient conditions and defined classes

Meat pizza **implies** having meat as ingredient (and being pizza).

A pizza with meat as ingredient **implies** being a meat pizza.

Hawaiian pizzas have ham as ingredient and thus they are meat pizzas.



# Detecting modelling errors

- Ice cream **implies** having fruit as topping
- Ice cream is **disjoint with** Pizza
- The domain of has topping is pizza, that is, having any topping **implies** being a pizza.
- Domain is a type of sufficient condition, global scope for the property.

Description: IceCream

Equivalent To +

- owl:Nothing

SubClass Of +

- Food
- hasTopping some FruitTopping

Disjoint With +

- PizzaTopping, Pizza, PizzaBase

Description: hasTopping

Equivalent To +

SubProperty Of +

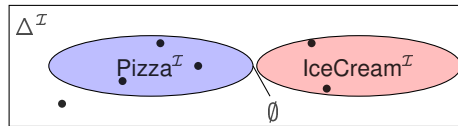
- hasIngredient
- inverse (isIngredientOf)

Inverse Of +

- isToppingOf

Domains (intersection) +

- Pizza

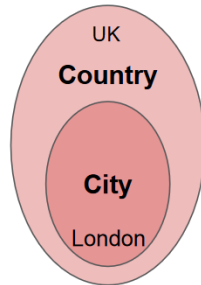
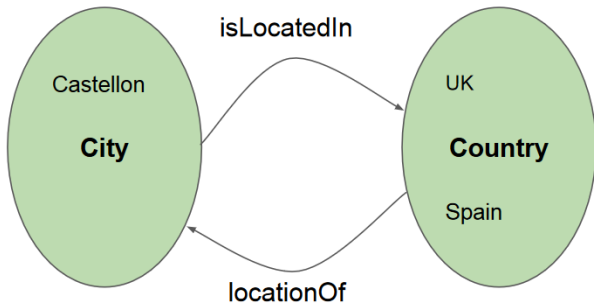


# Common mistakes: part-of VS subclass-of (i)

City **subClassOf** isLocatedIn some Country

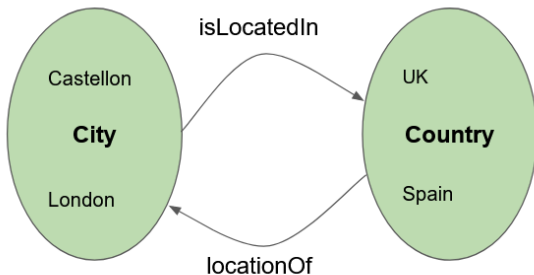
✖ Rectangular Snip

City **subClassOf** Country



## Common mistakes: part-of VS subclass-of (i)

City **subClassOf** isLocatedIn **some** Country

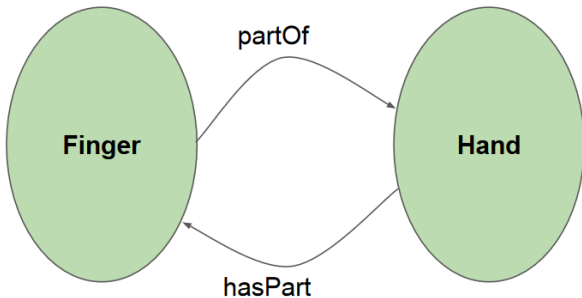


~~City **subClassOf** Country~~

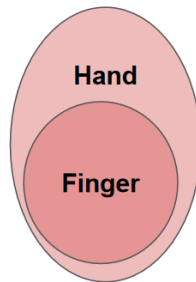


## Common mistakes: part-of VS subclass-of (ii)

Finger **subClassOf** partOf some Hand

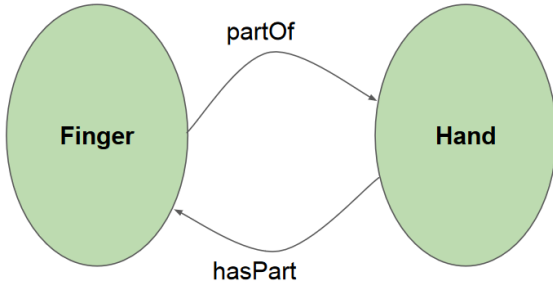


Finger **subClassOf** Hand

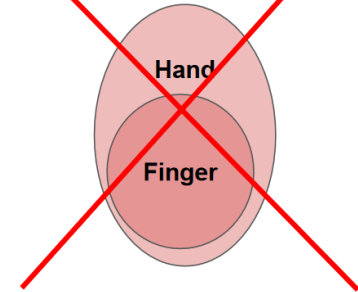


## Common mistakes: part-of VS subclass-of (ii)

Finger **subClassOf** partOf some Hand



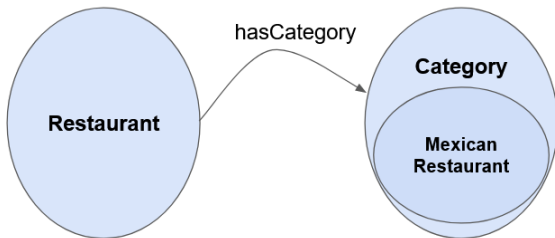
~~Finger **subClassOf** Hand~~



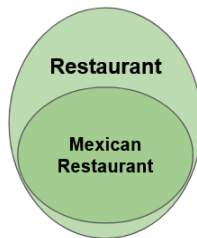


## Common mistakes: part-of VS subclass-of (iii)

Restaurant **subClassOf** hasCategory **some** Category

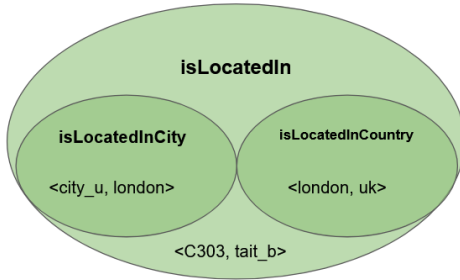


Mexican\_Restaurant **subClassOf** Restaurant

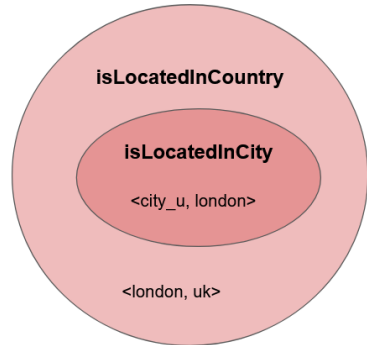


# Common mistakes: property hierarchy

isLocatedInCity **subPropertyOf** isLocatedIn  
isLocatedInCountry **subPropertyOf** isLocatedIn

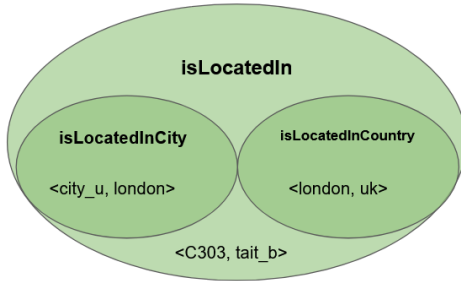


isLocatedInCity **subPropertyOf** isLocatedInCountry

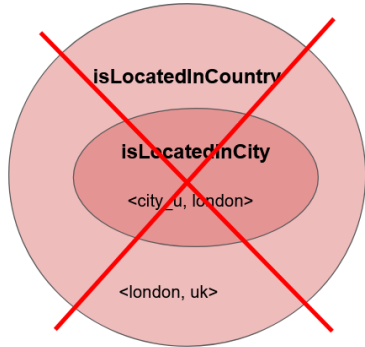


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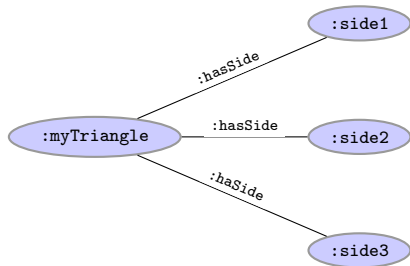


isLocatedInCity **subPropertyOf**  
isLocatedInCountry



## OWL 2 and Open World Assumption

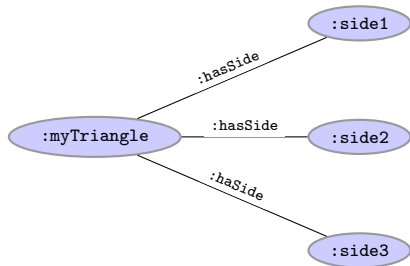
- `:Triangle EquivalentTo :hasSide exactly 3 :Side`



- is `:myTriangle` a `:Triangle`?

## OWL 2 and Open World Assumption

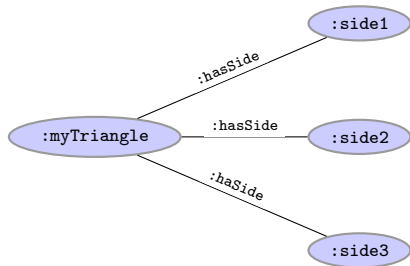
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## OWL 2 and Open World Assumption

- `:Triangle EquivalentTo :hasSide exactly 3 :Side`



- is `:myTriangle` a `:Triangle`? **I don't know** because of OWA and NUNA.
- **Solution:** deductive reasoning complemented with SPARQL queries (in this case with aggregates) → SPARQL assumes a CWA.

---

# Graph Database Solutions

# How to store Graph models?

- Relational model
  - Single table with 3 columns (source, edge, target)
  - Property tables (one table per type of entity, *e.g.*, Person, Module)
  - Binary tables (one table per relationship, *e.g.*, source, target)

M. Wylot and others. RDF Data Storage and Query Processing Schemes. ACM Computing Surveys 2018



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  - Binary tables (one table per relationship, *e.g.*, source, target)
- **Graph-based databases** (NoSQL)

M. Wylot and others. RDF Data Storage and Query Processing Schemes. ACM Computing Surveys 2018

# Graph database solutions

- Scale to large Knowledge Graphs.
- Sophisticated indexing structures.
- Optimised reasoning.
- Fast query performance.
- Server solution in production.

# State-of-the-art solutions

Dimensions:

- Free version.
- Compliance with Semantic Web standards.
- Reasoning capabilities.
- In-memory or In-disk.
- Documentation and installation requirements.
- Additional features.

A Survey of RDF Stores & SPARQL Engines for Querying Knowledge Graphs. arXiv:2102.13027 2021 (Appendix A)

# Semantic Web standards

- The **World Wide Web Consortium (W3C)** is an international community that develops open standards to ensure the long-term growth of the Web: <https://www.w3.org/>
- On the Web and **beyond**.
- **Why standards?**
  - broader industry (and academic) agreement,
  - interoperability across organizations and applications,
  - avoids vendor lock-in of a particular (exchange or query) format.

# Apache Jena TDB

- Free solution.
- Provides a native (in-disk) RDF store.
- In combination with Jena Fuseki to provide SPARQL Endpoint support.
- ✗ Supports reasoning as in Jena, but not direct support for OWL 2 nor the OWL 2 profiles.

<https://jena.apache.org/documentation/tdb/>

# OpenLink Virtuoso

- ✓ Provides the SPARQL endpoint for DBpedia.
  - Open source and commercial versions.
  - Object-oriented database model.
- ✓ Native graph model storage provider for Jena and RDF4J.
- ✗ Custom inference rules. Partial support for OWL 2.

`https://virtuoso.openlinksw.com/`

`http://vos.openlinksw.com/owiki/wiki/VOS`

# Blazegraph

- ✓ Provides the SPARQL Endpoint for Wikidata.
- ✓ Free and open source.
  - Both in-memory and disk-oriented storage.
- ✗ Only supports OWL 1 Lite reasoning.
  - Blazegraph team now working for Amazon.

<https://blazegraph.com/>

# AllegroGraph

- Free and commercial licenses.
- ✓ Support for OWL 2 RL materialization.
- ✓ Client interface in several languages.
- Can be used to query both documents and graph data (via SPARQL).

<https://allegrograph.com/>



# Neo4j

- ✓ Open source graph database.
  - Based on the Property Graph Model.
- ✗ Cypher as graph query language (no native SPARQL support).
  - Support *via a plugin* for RDF, RDFS and OWL vocabularies.
- ✗ Basic inferencing support.
- ✓ Support for Analytics.
- ✓ Interfaces in many languages.

<https://neo4j.com/>

## GraphDB (formerly OWLIM)

- Free and commercial versions.
- ✓ Very easy to install and use.
- ✓ Powerful reasoning features: including OWL 2 QL and RL profiles.
- ✓ Supports SHACL validation.
- Includes text indexing via lucene.
- Powered the early Linked Data services at the BBC.

<https://www.ontotext.com/products/graphdb/>

# RDFox

- Commercial system. Free academic license on request.
- ✓ Support for materialization-based datalog reasoning (including OWL 2 RL and SWRL rules).
- ✓ Supports SHACL validation.
- In-memory RDF engine.
- ✓ Access via Java API or remotely via REST API or SPARQL Endpoint.
- ✗ Limitation on the size of the memory.

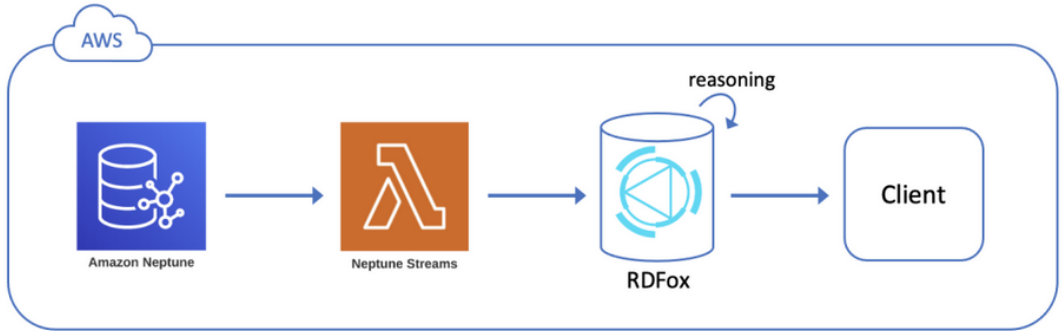
<https://www.oxfordsemantic.tech/product>

# Amazon Neptune

- Cloud-based only solution.
- Blazegraph is now part of Amazon Neptune.
- ✗ On-Demand pricing.
- ✗ Native inferencing is not yet supported.
- ✓ Keep an eye on future development!

<https://aws.amazon.com/neptune/>

# Amazon Neptune + RDFox



**Amazon Neptune and RDFox:** <https://aws.amazon.com/blogs/database/use-semantic-reasoning-to-infer-new-facts-from-your-rdf-graph-by-integrating-rdfox-with-amazon-neptune/>

# Graph database/Triplestore benchmarking

- Oracle Database 12c: 1.08 Trillion triples
- AnzoGraph DB: 1.06 Trillion triples
- AllegroGraph: 1.0 Trillion triples
- Virtuoso: 94.2 Billion Triples
- Stardog: 50 Billion triples
- **RDFox**: 19.47 Billion triples
- **GraphDB**: 17 Billion triples
- Apache Jena TBD: 16.7 billion triples.

Numbers may not be up-to-date: <https://www.w3.org/wiki/LargeTripleStores>

<https://medium.com/wallscope/comparison-of-linked-data-triplestores-a-new-contender-c62ae04901d3>

<https://medium.com/wallscope/comparing-linked-data-triplestores-ebfac8c3ad4f>

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# Laboratory: Hands-on SPARQL

# SPARQL: local and remote KG access

