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OWL 2 Profiles, SPARQL 1.1 and Entailment Regimes

Ernesto Jiménez-Ruiz Lecturer in Artificial Intelligence

Before we start...

Where are we?

- ✓ Introduction.
- ✓ RDF-based knowledge graphs.
- ✓ SPARQL 1.0
- ✓ RDFS Semantics and RDF(S)-based knowledge graphs.
- ✓ OWL (2) ontology language. Focus on modelling.
- ✓ Application to Data Science.

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7. **OWL 2 Profiles, SPARQL 1.1 and Entailment Regimes** (today).

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7. **OWL 2 Profiles, SPARQL 1.1 and Entailment Regimes** (today).
8. Ontology Alignment (March 17)
9. Machine Learning and Knowledge Graphs (March 24).
10. Graph Database Solutions and Invited Talks (March 31).

OWL 2 Reasoning and Profiles

Recap: OWL (The Web Ontology Language)

- A **W3C recommendation**:
  - OWL 1 (2004): `http://www.w3.org/TR/owl-ref/`
  - OWL 2 (2009): `https://www.w3.org/TR/owl2-overview/`

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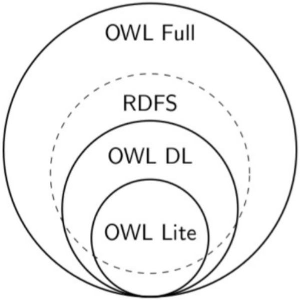
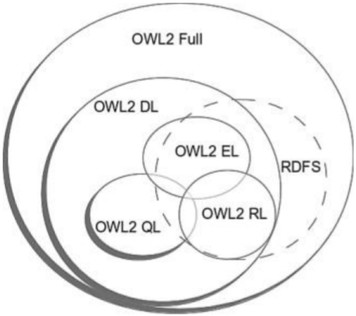
  - OWL 2 (2009): `https://www.w3.org/TR/owl2-overview/`
- OWL semantics based on **Description Logics (DL)**.
  - Family of knowledge representation languages
  - Decidable subset of First Order logic (FOL)
  - Original called: **Terminological language** or **concept language**

Recap: OWL 1, OWL 2 (profiles) and RDFS



OWL 1



OWL 2

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

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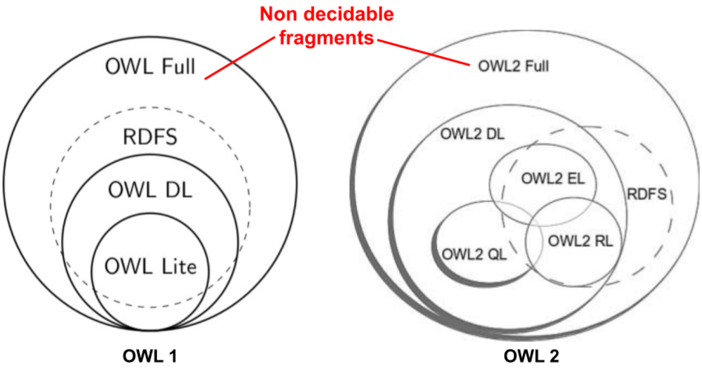

† **Reasoning in OWL 2** will partially get the same consequences as in the RDFS inference rules and many more.

Recap: Automated Reasoning

- Formal semantics allows the automatic deduction of **new facts**.
- Also allows us to perform checks that aim to detect the **correctness** of the designed model (*e.g.*, `:dolphin` is a `:Fish`?).

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  - `:Mammal` and `:Fish` are disjoint classes.
  - `:dolphin` cannot be an individual (or a subclass) of both `:Mammal` and `:Fish`.

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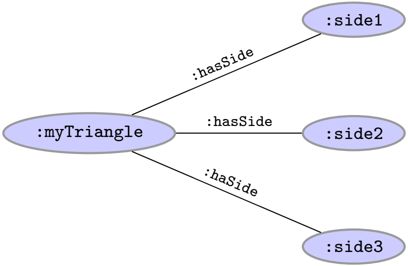
  - `:dolphin` cannot be an individual (or a subclass) of both `:Mammal` and `:Fish`.
- Extremely valuable for designing **correct** ontologies/KGs, specially when working **collaboratively** and **integrating** various sources.

Recap: OWL 2 and Open World Assumption

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



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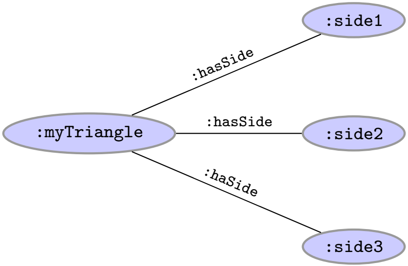

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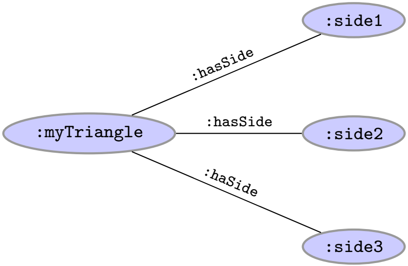

– is `:myTriangle` a `:Triangle`? No, because of OWA and NUNA.

– Solution: reasoning in OWL can be complemented with SPARQL queries (in this case with aggregates) $\rightarrow$ SPARQL 1.1

Recap: OWL 2 Axioms into Boxes

- Traditionally OWL 2 axioms are put in boxes.
- The **TBox** (terminological knowledge)
  - Typically independent of any actual instance data.
  - Property axioms are also referred to as **RBox**
- The **ABox** (assertional knowledge)
  - Contains facts about concrete instance.

OWL 2 TBox Reasoning

(Standard) Reasoning tasks that use only the TBox $\mathcal{T}$†

– Concept **unsatisfiability**: Given C, does $\mathcal{T} \models C \sqsubseteq \bot$? (*i.e.*, $C^{\mathcal{I}} = \emptyset$)

† **(Model-Theoretic Semantics)** The answer to 'does $\mathcal{T} \models \alpha$?' will be positive if for each interpretation $\mathcal{I}$ such that $\mathcal{I} \models \mathcal{T}$, $\mathcal{I} \models \alpha$ too.

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– Concept **disjointness**: Given C and D, does $\mathcal{T} \models C \sqcap D \sqsubseteq \bot$? (*i.e.*, $\mathcal{C}^\mathcal{I} \cap \mathcal{D}^\mathcal{I} \subseteq \emptyset$)

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- Conjunctive Query Answering (**SPARQL**).

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OWL 2 Reasoning Algorithms

- Reasoning in OWL 2 is typically based on **(Hyper)Tableau Reasoning Algorithms** (tableau = truth tree)
- Reasoning tasks **reduced to (un)satisfiability**.
- Algorithm tries to construct an **abstraction** of a model.

Chapter 5: Foundations of Semantic Web Technologies. CRC Press 2009
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– State-of-the-art algorithms:
  – *e.g.*, **HermiT** (default option in Protégé).
  – Implement a number of (search) **optimisations**.
  – **Effective** with many realistic ontologies

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Tractability Problems with OWL 2 Reasoning

- Problems with **very large** and/or **cyclical ontologies**.
  - Ontologies may define hundred of thousands of terms (*e.g.*, SNOMED CT)
  - Large number of tests for classification (each test can lead to the construction of very large models).

Computational properties: `https://www.w3.org/TR/owl2-profiles/#Computational_Properties`
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  - Large number of tests for classification (each test can lead to the construction of very large models).
- Problems with **medium/large** data sets (ABoxes)
  - OWL 2 Reasoners typically optimized for TBox reasoning tasks.
  - Data also brings additional complexity.

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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.

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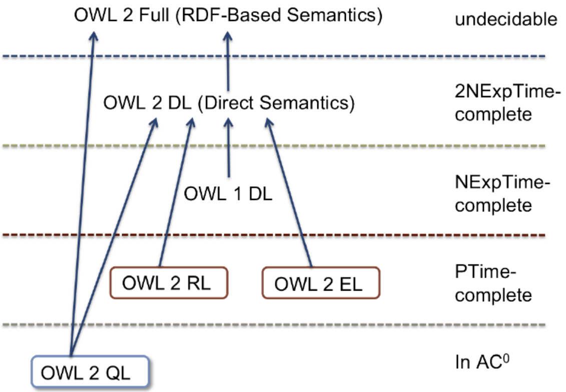
Data Complexity OWL 2 Profiles



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

OWL EL profile (i)

Based on the DL $\mathcal{EL}^{++}$. Concept descriptions, simplified

$$
\begin{array}{lll}
C, D \rightarrow & A & \mid \quad \text{(atomic concept)} \\
& \top & \mid \quad \text{(universal concept)} \\
& \bot & \mid \quad \text{(bottom concept)} \\
& \{a\} & \mid \quad \text{(\textit{singular} enumeration)} \\
& C \sqcap D & \mid \quad \text{(intersection)} \\
& \exists R.C & \mid \quad \text{(existential restriction)}
\end{array}
$$

Axioms

- $C \sqsubseteq D$ and $C \equiv D$ for concept descriptions D and C.
- $P \sqsubseteq Q$ and $P \equiv Q$ for roles P, Q. Also Domain and Range.
- $C(a)$ and $R(a, b)$ for concept C, role R and individuals a, b.

OWL EL Profile (ii)

- ✓ Standard reasoning tasks in P time
- ✓ Very good for large ontologies.
- ✓ Used in many biomedical ontologies (*e.g.*, SNOMED CT).

Not supported features, simplified:

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

OWL EL Profile (iii)

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

$$\frac{A \sqsubseteq B \qquad B \sqsubseteq C}{A \sqsubseteq C}$$

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

† 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`

OWL QL Profile (i)

Based on DL-Lite$_R$. Concept descriptions, simplified

$$
\begin{array}{rlll}
C, C' \rightarrow & A & | & \text{(atomic concept)} \\
& \exists R.\top & | & \text{(existential restriction with } \top \text{ only)} \\
D, D' \rightarrow & A & | & \text{(atomic concept)} \\
& \exists R.D & | & \text{(existential restriction)} \\
& \neg D & | & \text{(negation)} \\
& D \sqcap D' & | & \text{(intersection)}
\end{array}
$$

Axioms

– $C \sqsubseteq D$ for concept descriptions D and C (and $C \equiv C'$).

– $P \sqsubseteq Q$ and $P \equiv Q$ for roles P, Q. Also Domain and Range.

– $C(a)$ and $R(a, b)$ for concept C, role R and individuals a, b.

OWL QL Profile (ii)

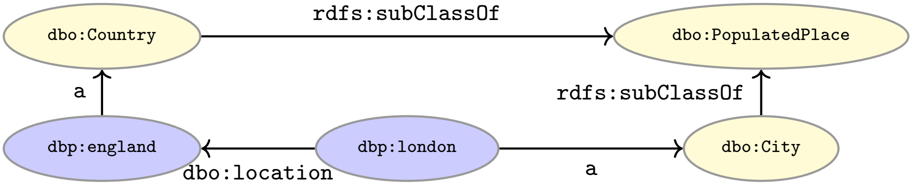
- ✓ Required language so that queries can be rewritten and then translated to SQL.
- ✓ Used in Ontology Based Data Access (OBDA).

Not supported, simplified:

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

OWL QL Profile (iii)

– Reasoning is performed via backward chaining (*e.g.*, rewriting of a given query Q into Q' via the ontology axioms). For example:



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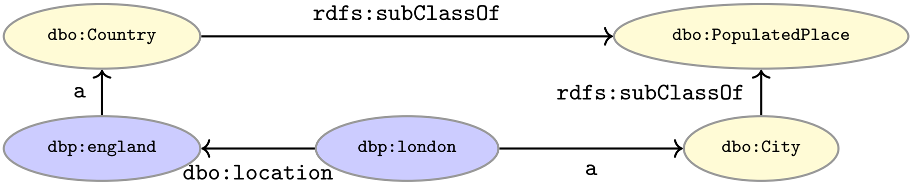

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Q':
```
SELECT DISTINCT ?place WHERE {
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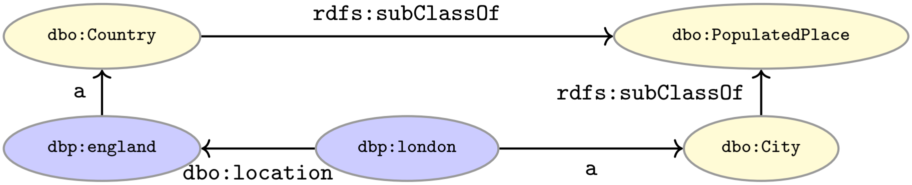
    UNION {?place rdf:type dbo:Country .}
    UNION {?place rdf:type dbo:City .}  }
```



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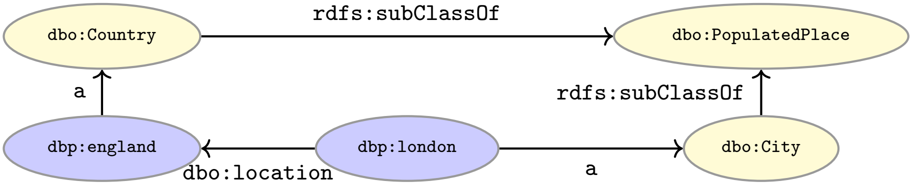
```

Q' Result= {dbp:england, dbp:london}



OWL 2 RL Profile (i)

Based on Description Logic Programs (DLP). Concept descriptions:

$$
\begin{array}{rlcl}
C, C' \rightarrow & A & \mid & \text{(atomic concept)} \\
& C \sqcap C' & \mid & \text{(intersection)} \\
& C \sqcup C' & \mid & \text{(union)} \\
& \exists R.C & \mid & \text{(existential restriction)} \\
D, D' \rightarrow & A & \mid & \text{(atomic concept)} \\
& D \sqcap D' & \mid & \text{(intersection)} \\
& \forall R.D & \mid & \text{(universal restriction)}
\end{array}
$$

Axioms

- $C \sqsubseteq D$, $C \equiv C'$, $\top \sqsubseteq \forall R.D$, $\top \sqsubseteq \forall R^{-}.D$ $R \sqsubseteq P$, $R \equiv P^{-}$ and $R \equiv P$ for roles R, P and concept descriptions C, C' and D. Also Domain and Range.
- $C(a)$ and $R(a, b)$ for concept C, role R and individuals a, b.

OWL 2 RL Profile (ii)

- ✗ 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.

OWL 2 RL Profile (iii)

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

$$\frac{\texttt{p1 owl:inverseOf p2 .} \qquad \texttt{?x ?p1 ?y .}}{\texttt{?y ?p2 ?x .}}$$

W3C: `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`
RDFox: A Highly-Scalable RDF Store. ISWC 2015. `https://www.oxfordsemantic.tech/product`

SPARQL 1.1

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
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  - **SPARQL 1.0:** W3C Recommendation 15 January 2008
  - **SPARQL 1.1:** W3C Recommendation 21 March 2013
- In this lecture we will learn about the extensions in SPARQL 1.1.
- Documentation:
  - Syntax and semantics of the SPARQL query language for RDF.
    `https://www.w3.org/TR/sparql11-overview/`

Recap: Components of a SPARQL (1.0) query

```
PREFIX foaf:  <http://xmlns.com/foaf/0.1/>
PREFIX dbo:  <http://dbpedia.org/ontology/>
SELECT DISTINCT ?costar
FROM <http://dbpedia.org>
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
```

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Prologue: prefix definitions

```
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```

Recap: Components of a SPARQL (1.0) query

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

```
PREFIX foaf:  <http://xmlns.com/foaf/0.1/>
PREFIX dbo:  <http://dbpedia.org/ontology/>
SELECT DISTINCT ?costar
FROM <http://dbpedia.org>
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
```

Recap: Components of a SPARQL (1.0) query

Dataset specification

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

Recap: Components of a SPARQL (1.0) query

Query pattern: graph pattern to be matched + filters

```
PREFIX foaf:  <http://xmlns.com/foaf/0.1/>
PREFIX dbo:  <http://dbpedia.org/ontology/>
SELECT DISTINCT ?costar
FROM <http://dbpedia.org>
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
```

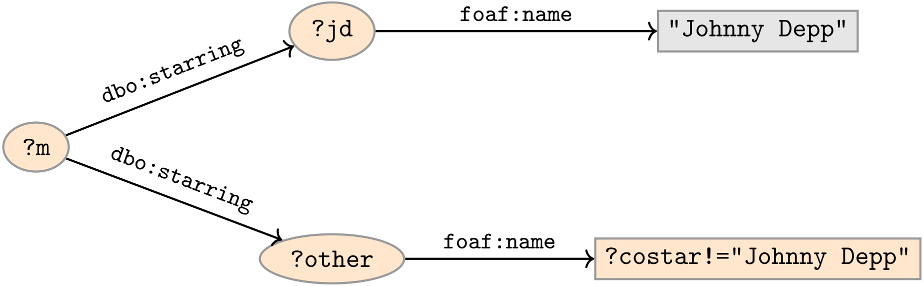
Recap: Components of a SPARQL (1.0) query

Solution modifiers: ORDER BY, LIMIT, OFFSET

```
PREFIX foaf:  <http://xmlns.com/foaf/0.1/>
PREFIX dbo:  <http://dbpedia.org/ontology/>
SELECT DISTINCT ?costar
FROM <http://dbpedia.org>
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
```

Recap: Graph Patterns

The previous SPARQL query pattern as a graph:



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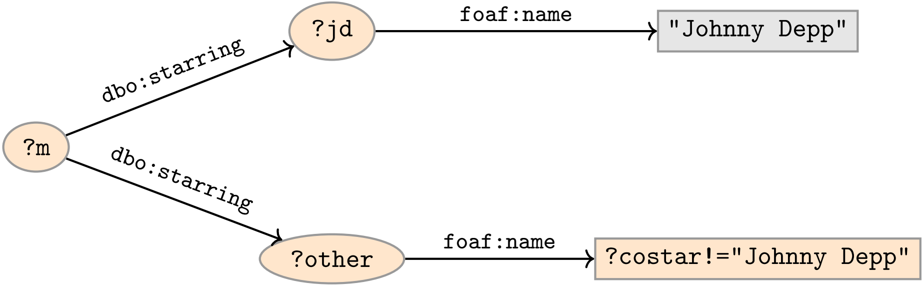

Pattern matching: assign values to variables to make this a sub-graph of the RDF graph.

SPARQL 1.1: new fatures

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

SPARQL 1.1: new fatures

- The new features in **SPARQL 1.1 QUERY language**:
  - Assignments and Expressions
  - Aggregates
  - Subqueries
  - Negation
  - 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 <http://dbpedia.org/ontology/PopulatedPlace/areaTotal> ?area .
  ?city dbo:country <http://dbpedia.org/resource/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 ?count)
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 ?count)
WHERE {
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    ?movie dbo:starring ?actor .
}
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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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```
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(?population)
```

Negation in SPARQL 1.0

COMBINING OPTIONAL, FILTER and !BOUND:

People without names

```
SELECT DISTINCT * WHERE {
    ?person a foaf:Person .
    OPTIONAL {
        ?person foaf:name ?name .
    FILTER (!bound(?name))
    }
}
```

However, this is not very easy to write.

Negation in SPARQL 1.1: MINUS and FILTER NOT EXISTS

Two ways to do negation:

```
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 }
}
```

†Negation assumes CWA and UNA

Property paths: basic motivation

- Some queries get needlessly large.
- SPARQL 1.1 define a small language to defined paths.
- Examples:
  - `uio:Ernesto foaf:knows+ ?friend` to extract all friends of friends.
  - `foaf:maker|dct: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: syntax

Syntax Form	Matches
`iri`	An (property) IRI. A path of length one.
`^elt`	Inverse path (object to subject).
`elt1 / elt2`	A sequence path of `elt1` followed by `elt2`.
`elt1 | elt2`	A alternative path of `elt1` or `elt2` (all possibilities are tried).
`elt*`	Seq. of zero or more matches of `elt`.
`elt+`	Seq. of one or more matches of `elt`.
`elt?`	Zero or one matches of `elt`.
$\texttt{!iri or !(iri}_1\texttt{\| ...\|iri}_n\texttt{)}$	Negated property set.
$\texttt{!\^{}iri or !(\^{}iri}_i\texttt{\| ...\|\^{}iri}_n\texttt{)}$	Negation of inverse path.
$\texttt{!(iri}_1\texttt{\|...\|iri}_j\texttt{\|\^{}iri}_{j+1}\texttt{\|...\|\^{}iri}_n\texttt{)}$	Negated combination of forward and inverese properties.
`(elt)`	A group path `elt`, brackets control precedence.

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

SPARQL 1.1 Entailment Regimes

OWL 2 Entailment regimes: overview

- Gives guiadance for SPARQL query engines
- Basic graph pattern by means of subgraph matching: *simple entailment*
- Solutions that implicitly follow from the queried graph: *entailment regimes*
- **RDF entailment**, **RDF Schema entailment**, D-Entailment, **OWL 2 RDF-Based Semantics entailment**, **OWL 2 Direct Semantics entailment**, and RIF-Simple entailment
- `https://www.w3.org/TR/2013/REC-sparql11-entailment-20130321/`

OWL 2 Entailment regimes: overview

OWL 2 RDF-based Semantics Entailment Regime

- Direct extension of the RDFS semantics
- Interprets RDF triples directly without the need of mapping an RDF graph into OWL objects.
- Incomplete for OWL 2 and undecidable for OWL 2 Full.

OWL 2 Direct Semantics Entailment Regime

- Decidable if some restrictions are imposed to the RDF graph and SPARQL queries.

OWL 2 Entailment Regimes: Complexity and Profiles

– Entailment under **OWL 2 (DL) Direct Semantics** entailment is decidable, but computationally hard.

OWL 2 Entailment Regimes: Complexity and Profiles

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- No Direct Semantics for OWL 2 Full.
- **Direct Semantics for OWL 2 QL and EL** Profiles have very nice computational properties.
- Entailment under **OWL 2 QL and EL RDF-based semantics** is incomplete as well.

OWL 2 Entailment Regimes: Complexity and Profiles (cont.)

– **OWL 2 RL** defines a syntactic subset of OWL 2. For RDF graphs that fall into this syntactic subset:

OWL 2 Entailment Regimes: Complexity and Profiles (cont.)

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- **OWL 2 RL** defines a syntactic subset of OWL 2. For RDF graphs that fall into this syntactic subset:
  - Direct Semantics and RDF-based Semantics yield the same (**complete and sound**) results.
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OWL 2 Entailment Regimes: Complexity and Profiles (cont.)

- **OWL 2 RL** defines a syntactic subset of OWL 2. For RDF graphs that fall into this syntactic subset:
  - Direct Semantics and RDF-based Semantics yield the same (**complete and sound**) results.
  - For Direct Semantics the input RDF graph has to satisfy some constrains.
  - The RDF-Based semantics can be use with any RDF graph.

Laboratory Session

Laboratory

- Small exercise about OWL 2 RL entailment (very similar to RDFS Semantics).
- SPARQL 1.1 queries
- We are using OWL 2 RL reasoning (or similar in Jena). What if the modelled ontology is not in this profile?
- About lab 6 solution.
- Global picture.

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- Dr. Valentina Tamma (University of Liverpool)
  - `Comp 318 - Advanced Web Technologies`
  - `https://cgi.csc.liv.ac.uk/~valli/Comp318.html`