TECHNISCHE UNIVERSITÄT DRESDEN

FOUNDATIONS OF SEMANTIC WEB TECHNOLOGIES

SPARQL Entailment Regimes

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DRESDEN concept
Exzellenz aus Wissenschaft und Kultur

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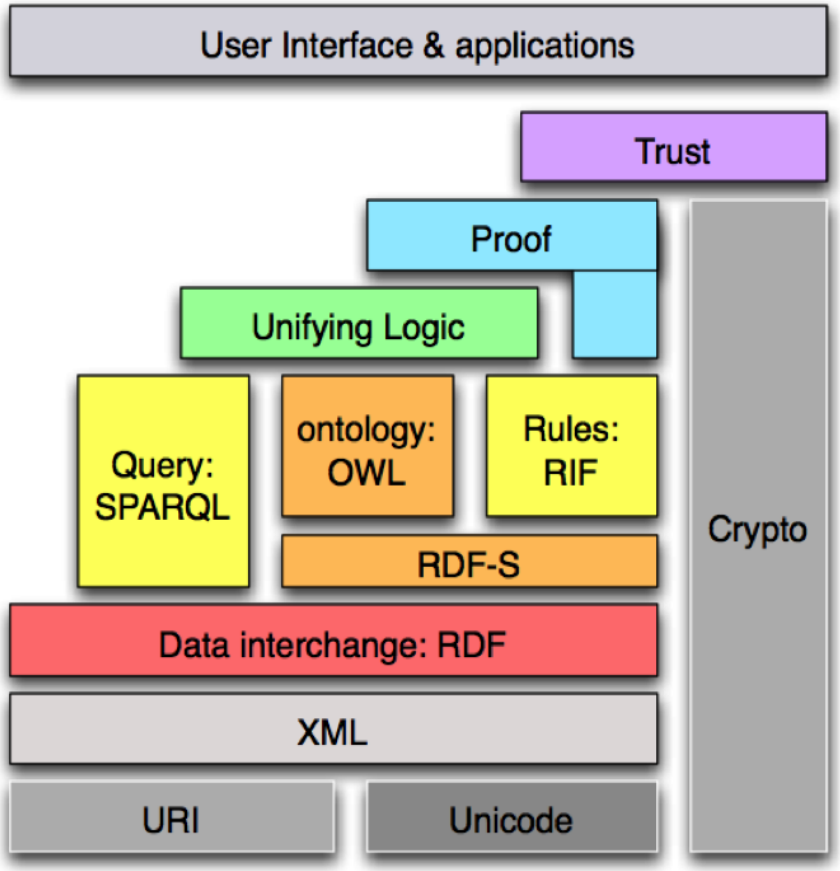
The SPARQL Query Language



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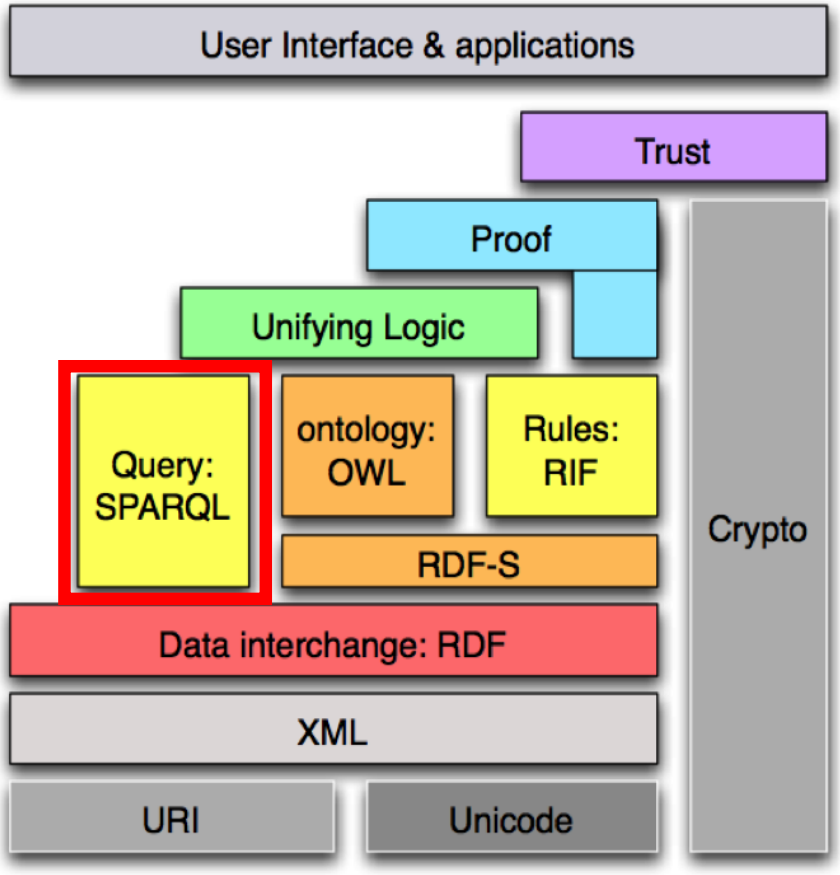

Agenda

1. Introduction and Motivation
2. Conditions for Extending the Bgp Operator
3. BGP Evaluation with RDFS Entailment
4. Implementation Options
5. BGP Evaluation with OWL Semantics
6. Summary

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Introduction and Motivation

Query

```
SELECT ?x WHERE { ?x a ex:Person }
```

Data

```
ex:Birte ex:presentsLecture "SPARQL" .
ex:presentsLecture rdfs:domain ex:Lecturer .
ex:Lecturer rdfs:subClassOf ex:Person .
```

- No answer using simple entailment/subgraph matching

SPARQL with Implicit Solutions

- So far: solutions through subgraph matching (simple entailment)
- Only the Bgp(·) algebra operator (exception: property paths) generates solutions
- SPARQL 1.0 specifies a BGP matching extension point to overwrite behaviour of Bgp(·)

Idea: Instead of subgraph matching use entailment relations

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Previous BGP Evaluation

Definition (Solution)

Let P be a basic graph pattern. A partial function μ is a solution for Bgp(P) over the queried (active) graph G if:

1. the domain of μ is exactly the set of variables in P,
2. there exists an assignment σ from blank nodes in P to IRIs, blank nodes, or RDF literals in G such that:
3. the RDF graph $\mu(\sigma(P))$ is a subgraph of G.

The result $[\![\text{Bgp}(P)]\!]_G$ of the evaluation of Bgp(P) over G is the multi set of solutions μ (multiplicity corresponds to the number of different assignments)

Naive Idea for BGP Evaluation using RDFS Entailment

Definition (Solution)

Let P be a basic graph pattern. A partial function μ is a solution for Bgp(P) over the queried (active) graph G under RDFS entailment if:

1. the domain of μ is exactly the set of variables in P,
2. there exists an assignment σ from blank nodes in P to IRIs, blank nodes, or RDF literals such that:
3. the RDF graph $\mu(\sigma(P))$ is RDFS-entailed by G.

The result $[\![\text{Bgp}(P)]\!]_G$ of the evaluation of Bgp(P) over G under RDFS entailment is the multi set of such solutions

Conditions for Entailment Regimes (1)

- The naive idea produces not always intuitive results
- It is not that simple since such extensions have to satisfy several conditions

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1. RDF Graphs that are well-formed for the regime
2. an entailment relation between well-formed graphs

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1. RDF Graphs that are well-formed for the regime
2. an entailment relation between well-formed graphs

We can address this:

1. For RDF(S) all RDF graphs are ok, for OWL we will further define well-formed graphs
2. We can use already defined entailment relations

Conditions for Entailment Regimes (2)

An entailment regime E defines furthermore

3. The effect of a query over an inconsistent graph
4. Conditions to guarantee the uniqueness of the results modulo blank node labels

We can also address this:

3. Warning/error
4. Automatically satisfied for RDFS entailment

Conditions for Entailment Regimes (3)

An entailment regime E defines furthermore

5. Conditions such that for any basic graph pattern P and any graph G, if $\mu_1, \ldots, \mu_n \in [\![P]\!]^{\mathsf{E}}_{\mathsf{G}}$ and $P_1, \ldots, P_n$ are copies of P not sharing any blank nodes with G or with each other:
   $G \models^E (G \cup \mu_1(P_1) \cup \ldots \cup \mu_n(P_n))$
6. Condition to prevent trivial infinite solutions

Condition 5 makes sure that blank nodes in solutions correspond to blank nodes in the graph (no unintended co-references are introduced)

Comment for Condition 5

Example

G: `:a :b _:c .`
`_:d :e :f .`

G_1: `:a :b _:b1 .`
`_:b2 :e :f .`

G_2: `:a :b _:b2 .`
`_:b1 :e :f .`

G_3: `:a :b _:b1 .`
`_:b1 :e :f .`

- G has as simple consequences G_1 and G_2, but not G_3 (blank nodes are merged)

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- G has as simple consequences G_1 and G_2, but not G_3 (blank nodes are merged)
- Let `P = { :a :b ?x . ?y :e :f }`. We would have μ_1: `?x` $\mapsto$ `_:b1`, `?y` $\mapsto$ `_:b2` and μ_2: `?x` $\mapsto$ `_:b2`, `?y` $\mapsto$ `_:b1` as solutions for `P` over G since $\mu_1(\texttt{P}) = G_1$, $\mu_2(\texttt{P}) = G_2$

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- But $G \cup \mu_1(\texttt{P}) \cup \mu_2(\texttt{P})$ is not a consequence (contains G_3)

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- But $G \cup \mu_1(\texttt{P}) \cup \mu_2(\texttt{P})$ is not a consequence (contains G_3)
- Problem: we introduced unintended co-references

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Problems with the Naive Evaluation Idea (1)

Even an empty RDF Graph RDFS-entails infinitely many axiomatic triples:

- $\{\} \models_{\text{RDFS}}$ `rdf:_i rdf:type rdf:Property` for all $i \in \mathbf{N}$

Query

```
SELECT ?x WHERE { ?x rdf:type rdf:Property }
```

$\rightsquigarrow$ Query has infinitely many solutions under RDFS entailment

Solution (1)

- Bindings are limited to a finite vocabulary

Definition (Solution)

Let P be a basic graph pattern. A partial function μ is a solution for Bgp(P) over the queried (active) graph G under RDFS entailment if:

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4. the RDF graph $\mu(\sigma(P))$ is RDFS-entailed by G.

Problem with the Naive Evaluation Idea (2)

Taking only the vocabulary of G is too strict:

- `{ ex:s ex:p ex:o . ex:p rdfs:domain ex:C }` $\models_{\text{RDFS}}$ `{ ex:s rdf:type ex:C }`

Query

```
SELECT ?x WHERE { ex:s ?x ex:C }
```

Has no solutions (`rdf:type` $\notin$ Voc(G)).

Solution (2)

- Let $\text{Voc}^-(\text{RDFS}) = \text{Voc}(\text{RDFS}) \setminus \{\texttt{rdf:\_i} \mid i \in \mathbf{N}\}$

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Problems with the Naive Evaluation Idea (3)

Blank nodes have existential semantics

- `{ ex:s ex:p ex:o }` $\models_{\text{RDFS}}$ `{ ex:s ex:p _:id }` for each `id`

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  for each `id`

We already guarantee finite results since the possible range of μ and σ is finite, but . . .

Problems with the Naive Evaluation Idea (3)

Query

```
SELECT ?x WHERE { ex:s1 ex:p1 ?x }
```

Data

G_1 = { ex:s1 ex:p1 _:a }
G_2 = { ex:s1 ex:p1 _:a . ex:s2 ex:p2 _:b }

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- Has 1 solution for G_1 and 2 solutions for G_2

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- Solution: Skolemisation

Skolemisation

- Skolemisation: we consider the blank nodes as constants/normal IRIs

Definition (Skolemisation)

Let the prefix `skol` refer to a namespace IRI that does not occur as the prefix of any IRI in the queried (active) graph or query. The Skolemisation sk(_ :b) of a blank node _ :b is defined as sk(_ :b) = `skol`:b. We extend sk($\cdot$) to graphs in the natural way.

Example: Skolemisation

Query

```
SELECT ?x WHERE { ex:s1 ex:p1 ?x }
```

Data (Skolemised)

$sk(G_1)$ = `{ ex:s1 ex:p1 skol:a }`
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Only 1 Solution μ: `?x` $\mapsto$ `skol:a` for $sk(G_1)$ and $sk(G_2)$

Problems with Skolemisation

- Of course we do not want to see Skolem constants in solutions

$\rightsquigarrow$ Use Skolemisation only as a condition, applied to the graph and query

Solutions in the RDFS Entailment Regime

Definition (Solutions under RDFS entailment)

Let P be a basic graph pattern. A partial function μ is a solution for Bgp(P) over the queried (active) graph G under RDFS entailment if:

1. the domain of μ is exactly the set of variables in P,
2. terms in the range of μ occur in G or $\text{Voc}^-(\text{RDFS})$,
3. there exists an assignment σ from blank nodes in P to IRIs, blank nodes, or RDF literals in G such that:
4. the RDF graph $\text{sk}(\mu(\sigma(\mathtt{P})))$ is well-formed and RDFS-entailed by G.

The well-formed criterion prevents literals in subject position

SPARQL Entailment Regime

SPARQL entailment regimes define

- A name for the regime
- What entailment relation is used, e.g., RDFS-entailment
- Above described restrictions to address extension point conditions
- Legal graphs and queries (for RDFS all RDF graphs and SPARQL queries are legal)
- Handling of inconsistencies
- Errors handling
- How a regime can be described in SPARQL service descriptions

Standard SPARQL Semantics as Entailment Regime

Definition (Solutions under simple entailment)

Let P be a basic graph pattern. A partial function μ is a solution for Bgp(P) over the queried (active) graph G under ~~RDFS~~ simple entailment if:

1. the domain of μ is exactly the set of variables in P,
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$\rightsquigarrow$ Same definition can be used with simple entailment to obtain subgraph matching semantics

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Implementation of the RDFS Entailment Regime

The definition based on entailment relations allows for different implementation techniques

- Materialisation / forwards-chaining
- Query rewriting / backwards-chaining
- Hybrid approaches

RDFS Entailment Regime via Materialisation

Query

```
SELECT ?x WHERE { ?x a ex:Person }
```

Data

```
ex:Birte ex:presentsLecture "SPARQL" .
ex:presentsLecture rdfs:domain ex:Lecturer .
ex:Lecturer rdfs:subClassOf ex:Person .
```

- No answer under simple entailment/subgraph matching

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- No answer under simple entailment/subgraph matching
- Idea: we extend the queried graph with relevant inferred triples

RDFS Entailment Regime via Materialisation

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```

- Query over the extended graph: μ: `?x` $\mapsto$ `ex:Birte`

RDFS Entailment Regime via Materialisation

Query

```
SELECT ?x WHERE { ?x a ex:Person }
```

Data

```
ex:Birte ex:presentsLecture  "SPARQL" .
ex:presentsLecture rdfs:domain ex:Lecturer .
ex:Lecturer rdfs:subClassOf ex:Person .
ex:Birte rdf:type ex:Lecturer .
ex:Birte rdf:type ex:Person .
```

- Query over the extended graph: μ: `?x` $\mapsto$ `ex:Birte`
- Disadvantages:

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```

- Query over the extended graph: μ: `?x` $\mapsto$ `ex:Birte`
- Disadvantages:
  - Size of the queried graph grows
  - Each update requires recomputation of the closure (extension)

RDFS Ent. Regime via Query Rewriting

Query

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- Idea: extend the query rather than the queried graph

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- Idea: extend the query rather than the queried graph
- Rule rdfs9 produces a relevant consequence

$$\frac{\texttt{u rdfs:subClassOf x . v rdf:type u .}}{\texttt{v rdf:type x .}}\ \text{rdfs9}$$

RDFS Ent. Regime via Query Rewriting

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```
SELECT ?x WHERE { ?x a ex:Person  }  UNION
                { ?x a ex:Lecturer }
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```

- Rule rdfs2 produces now also a relevant consequence

$$\frac{\texttt{a rdfs:domain x . u a y .}}{\texttt{u rdf:type x .}}\ \text{rdfs2}$$

RDFS Ent. Regime via Query Rewriting

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```
SELECT ?x WHERE { ?x a ex:Person } UNION
                { ?x a ex:Lecturer } UNION
                { ?x ex:presentsLecture _:y }
```

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- Solution μ: `?x` $\mapsto$ `ex:Birte` (from 3. disjunct)

RDFS Ent. Regime via Query Rewriting

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- Solution μ: `?x` $\mapsto$ `ex:Birte` (from 3. disjunct)
- Disadvantages:
  - Hard/impossible to find all solutions (RDFS vocabulary used in unusual ways, queries not just for instances or subclasses)
  - Query Rewriting is done at run-time $\rightsquigarrow$ every query is evaluated a bit slower

Hybrid Approaches

- Combine materialisation and query rewriting
- Common (beyond RDFS): do not materialise `owl:sameAs`
- Extract schema part and use that for rewriting

Agenda

1 Introduction and Motivation

2 Conditions for Extending the Bgp Operator

3 BGP Evaluation with RDFS Entailment

4 Implementation Options

5 BGP Evaluation with OWL Semantics

6 Summary

SPARQL with OWL Direct Semantics

How can we use OWL's Direct Semantics with SPARQL?

1. Based on Description Logics
2. Semantics defined in terms of OWL structural objects
   - `owl:intersectionOf`, `ObjectIntersectionOf`, $\sqcap$
3. OWL DL ontologies can be mapped into RDF graphs
4. Not every RDF graph can be mapped into an OWL DL ontology

SPARQL with OWL Direct Semantics

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   - `?x rdfs:subPropertyOf ?y .`

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4. Variables can occur in class, property, individual, or literal positions
5. Definition of solutions analogously to the one for RDFS plus specification of well-formed BGPs and graphs

Implementation of the OWL DS Regime

- Materialisation impossible
- For example, we could have arbitrary disjunctions in the query (e.g., matching students that are not profs):

```
SELECT ?x WHERE { ?x a [ a owl:Class ;
owl:ObjectUnionOf ( ex:Student ex:Prof ) ] }
```

Implementation of the OWL DS Regime

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- For example, we could have arbitrary disjunctions in the query (e.g., matching students that are not profs):
  ```
  SELECT ?x WHERE { ?x a [ a owl:Class ;
  owl:ObjectUnionOf ( ex:Student ex:Prof ) ] }
  ```
- Turtle is not an easy syntax for complex OWL expressions
  ⇝ Usability problems
- Queries go beyond simple instance queries
- Optimisation is difficult for such complex queries

⇝ Often we have to test all possible bindings

SPARQL with OWL Profiles

OWL Profiles better suited for web applications

- OWL RL profile can be implemented via materialisation
- Polynomial complexity
- Extends RDFS semantics (i.e., can be used with OWL's RDF-Based Semantics)
- Works on arbitrary RDF graphs

Further Entailment Regimes

- RDF Entailment Regime (just simpler than RDFS)
- D-Entailment Regime (adds datatype reasoning to RDFS)
- RIF Core Entailment Regime
  - Specify rules and query an RDF graph plus the rules

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Summary

- SPARQL can now be used with RDF(S), OWL, and RIF semantics
- Entailment Regimes overwrite evaluation of basic graph patterns
- Property Paths from SPARQL Query 1.1 problematic
- Definition of solutions (relatively) general
  - Works also for subgraph matching/simple entailment
  - OWL's Direct Semantics needs extra conditions/definitions
- Implementation and efficiency for OWL problematic
  $\rightsquigarrow$ OWL 2 Profiles