SPARQL over RDF, and its possible extensions to RDFS

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Outline

- RDF and RDFS: A brief introduction
- SPARQL: A query language for RDF
  - Formal semantics
  - Complexity of the evaluation problem
  - Optimization methods
- SPARQL as a query language for RDFS
  - Formal semantics and the closure of an RDFS graph
- NAV-SPARQL: A navigational query language for RDFS

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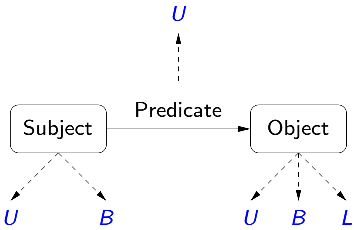
RDF in a nutshell

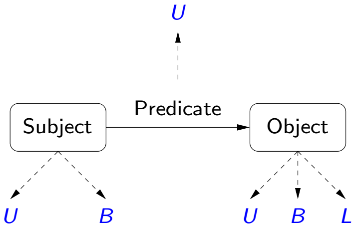
- RDF is the W3C proposal framework for representing information in the Web.
- Abstract syntax based on directed labeled graph.
- Schema definition language (RDFS): Define new vocabulary (typing, inheritance of classes and properties).
- Formal semantics.

RDF formal model



$$U = \text{set of Uris}$$
$$B = \text{set of Blank nodes}$$
$$L = \text{set of Literals}$$

RDF formal model



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$(s, p, o) \in (U \cup B) \times U \times (U \cup B \cup L)$ is called an RDF triple

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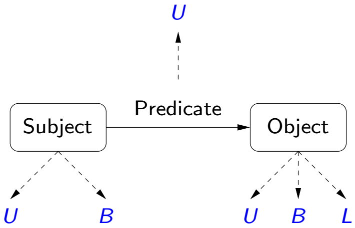

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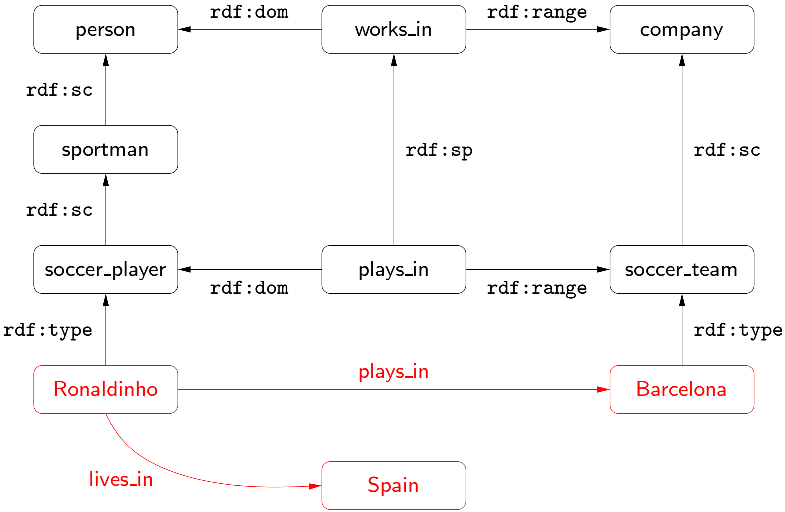
A set of RDF triples is called an RDF graph

RDF: An example



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Querying RDF: SPARQL

- SPARQL is the W3C candidate recommendation query language for RDF.
- SPARQL is a graph-matching query language.
- A SPARQL query consists of three parts:
  - Pattern matching: optional, union, nesting, filtering.
  - Solution modifiers: projection, distinct, order, limit, offset.
  - Output part: construction of new triples, ...

A simple RDF query language

```
SELECT ?Name ?Email
WHERE
{
  ?X :name ?Name
  ?X :email ?Email
}
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In general, in a query we have:

$$H \longleftarrow$$

- Head: processing of some variables.

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In general, in a query we have:

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In general, in a query we have:

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- Head: processing of some variables.
- Body: pattern matching expression.

We focus on P.

But things can become more complex ...

Interesting features of pattern matching on graphs

- Grouping
- Optional parts
- Nesting
- Union of patterns
- Filtering

```
{ P1
  P2 }
```

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```
{ { P1
    P2 }


  { P3
    P4 }


}
```

But things can become more complex ...

Interesting features of pattern matching on graphs

- Grouping
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```
{ { P1
    P2
    OPTIONAL { P5 }  }

  { P3
    P4
    OPTIONAL { P7 }  }

}
```

But things can become more complex ...

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    P2
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      OPTIONAL { P8 }  }  }
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```

But things can become more complex ...

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```
{ { P1
    P2
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  { P3
    P4
    OPTIONAL { P7
      OPTIONAL { P8 }  }  }
}
UNION
{ P9 }
```

But things can become more complex ...

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{ { P1
    P2
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UNION
{ P9
  FILTER ( R ) }
```

A formal semantics for SPARQL

A formal approach would be beneficial for:

- Clarifying corner cases
- Helping in the implementation process
- Providing sound foundations

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In this presentation:

- A formal compositional semantics for SPARQL
- A study of the complexity of evaluating SPARQL
- Optimization procedures

A standard algebraic syntax

- Triple patterns: just triples + variables, without blanks

`?X :name "john"`	$(?X, \text{name}, \text{john})$

- Graph patterns: full parenthesized algebra

original SPARQL syntax	algebraic syntax
`{ P1 P2 }`	$(P_1 \text{ AND } P_2)$
`{ P1 OPTIONAL { P2 }}`	$(P_1 \text{ OPT } P_2)$
`{ P1 } UNION { P2 }`	$(P_1 \text{ UNION } P_2)$
`{ P1 FILTER ( R ) }`	$(P_1 \text{ FILTER } R)$

A standard algebraic syntax

- Explicit precedence/association

Example

```
{ t1
  t2
  OPTIONAL { t3 }
  OPTIONAL { t4 }
  t5
}
```

$$((((t_1 \text{ AND } t_2) \text{ OPT } t_3) \text{ OPT } t_4) \text{ AND } t_5)$$

Mappings: building block for the semantics

Definition

A mapping is a partial function from variables to RDF terms.

The evaluation of a pattern results in a set of mappings.

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The semantics of triple patterns

Given an RDF graph and a triple pattern t

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The evaluation of t is the set of mappings that

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Example

graph	triple	evaluation
(R_1, name, john)		
(R_1, email, J@ed.ex)	(?X, name, ?Y)	
(R_2, name, paul)		

	?X	?Y
μ_1:	R_1	john
μ_2:	R_2	paul

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	$?X$	$?Y$
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Compatible mappings

Definition

Two mappings are compatible if they agree in their shared variables.

Example

	?X	?Y	?Z	?V
μ_1 :	R_1	john		
μ_2 :	R_1		J@edu.ex	
μ_3 :			P@edu.ex	R_2

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- μ_2 and μ_3 are not compatible

Sets of mappings and operations

Let M_1 and M_2 be sets of mappings:

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- extending mappings in M_1 with compatible mappings in M_2

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Union: $M_1 \cup M_2$

- mappings in M_1 plus mappings in M_2 (set theoretical union)

Definition

Left Outer Join: $M_1 ⟕ M_2 = (M_1 \bowtie M_2) \cup (M_1 \smallsetminus M_2)$

Semantics of SPARQL operators

Let M_1 and M_2 be the result of evaluating P_1 and P_2.

Definition

The evaluation of:

$$
\begin{array}{rcl}
(P_1 \text{ AND } P_2) & \longrightarrow & \\
(P_1 \text{ UNION } P_2) & \longrightarrow & \\
(P_1 \text{ OPT } P_2) & \longrightarrow &
\end{array}
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\end{array}
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Simple example

Example

$$(R_1, \text{name}, \text{john})$$
$$(R_1, \text{email}, \text{J@ed.ex})$$
$$(R_2, \text{name}, \text{paul})$$

$$((?X, \text{ name}, ?Y) \text{ OPT } (?X, \text{ email}, ?E))$$

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$((?X,$ name, $?Y)$ OPT $(?X,$ email, $?E))$

$?X$	$?Y$
R_1	john
R_2	paul

$?X$	$?E$
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$?X$	$?Y$	$?E$
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$?X$	$?E$
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- from the Join

Simple example

Example

$(R_1, \text{name}, \text{john})$
$(R_1, \text{email}, \text{J@ed.ex})$
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$?X$	$?Y$
R_1	john
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$?X$	$?Y$	$?E$
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$?X$	$?E$
R_1	J@ed.ex

- from the Difference

Simple example

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$$((?X,\ \text{name},\ ?Y)\ \text{OPT}\ (?X,\ \text{email},\ ?E))$$

$?X$	$?Y$
R_1	john
R_2	paul

$?X$	$?Y$	$?E$
R_1	john	J@ed.ex
R_2	paul	

$?X$	$?E$
R_1	J@ed.ex

- from the Union

Boolean filter expressions (value constraints)

In filter expressions we consider:

- equality $=$ among variables and RDF terms
- unary predicate bound
- boolean combinations ($\wedge$, $\vee$, $\neg$)

Satisfaction of value constraints

A mapping satisfies:

- $?X = c$ if it gives the value c to variable $?X$
- $?X = ?Y$ if it gives the same value to $?X$ and $?Y$
- bound($?X$) if it is defined for $?X$

Definition

Evaluation of (P FILTER R): Set of mappings in the evaluation of P that satisfy R.

The evaluation problem

Input:

A mapping, a graph pattern, and an RDF graph.

Question:

Is the mapping in the evaluation of the pattern against the graph?

Evaluation of simple patterns is polynomial

Theorem

For patterns using only AND *and* FILTER *operators* (AND-FILTER *expressions), the evaluation problem is polynomial:*

$$O(\textit{size of the pattern} \times \textit{size of the graph}).$$

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Proof idea

- *Check that the mapping makes every triple to match.*
- *Then check that the mapping satisfies the* FILTERs.

Evaluation including UNION is NP-complete

Theorem

The evaluation problem is NP-complete for AND-FILTER-UNION *expressions.*

Evaluation including UNION is NP-complete

Theorem

The evaluation problem is NP-complete for AND-FILTER-UNION *expressions.*

Proof idea

- *Reduction from 3SAT.*
- $\neg$ bound *is used to encode negation.*

In general: Evaluation problem is PSPACE-complete

Theorem

For general patterns that include OPT *operator, the evaluation problem is PSPACE-complete.*

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Can we efficiently evaluate SPARQL queries in practice?

In general: Evaluation problem is PSPACE-complete

Theorem

For general patterns that include OPT *operator, the evaluation problem is PSPACE-complete.*

Can we efficiently evaluate SPARQL queries in practice?

- We need to understand how the complexity depends on the operators of SPARQL.

A simple normal from

Proposition (UNION Normal Form)

Every graph pattern is equivalent to one of the form

$$P_1 \text{ UNION } P_2 \text{ UNION } \cdots \text{ UNION } P_n$$

where each P_i is UNION*–free.*

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Graph pattern expressions are usually in this normal form.

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where each P_i *is* UNION*–free.*

Graph pattern expressions are usually in this normal form.

Corollary

The evaluation problem is polynomial for AND-FILTER-UNION *expressions in the UNION normal form.*

PSPACE-completeness: A stronger lower bound

Theorem

The evaluation problem remains PSPACE-complete for AND-FILTER-OPT *expressions.*

PSPACE-completeness: A stronger lower bound

Theorem

The evaluation problem remains PSPACE-complete for AND-FILTER-OPT *expressions.*

Proof idea

- *Reduction from QBF: A pattern encodes a quantified propositional formula*

$$\forall x_1 \exists y_1 \forall x_2 \exists y_2 \cdots \psi.$$

PSPACE-completeness: A stronger lower bound

Theorem

The evaluation problem remains PSPACE-complete for AND-FILTER-OPT *expressions.*

Proof idea

- *Reduction from QBF: A pattern encodes a quantified propositional formula*

$$\forall x_1 \exists y_1 \forall x_2 \exists y_2 \cdots \psi.$$

- *Nested* OPT*s are used to encode quantifier alternation.*

PSPACE-hardness: A closer look

Assume $\varphi = \forall x_1 \exists y_1 \, \psi$, where $\psi = (x_1 \vee \neg y_1) \wedge (\neg x_1 \vee y_1)$.

We generate G, P_φ and μ_0 such that μ_0 belongs to the answer of P_φ over G iff φ is valid:

G :

R_ψ :

P_ψ :

P_φ :

μ_0 :

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G : $\{(a, \mathtt{tv}, 0),\ (a, \mathtt{tv}, 1),\ (a, \mathtt{false}, 0),\ (a, \mathtt{true}, 1)\}$

R_ψ :

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G : $\{(a, \texttt{tv}, 0),\ (a, \texttt{tv}, 1),\ (a, \texttt{false}, 0),\ (a, \texttt{true}, 1)\}$

R_ψ : $((?X_1 = 1 \vee ?Y_1 = 0)\ \wedge\ (?X_1 = 0 \vee ?Y_1 = 1))$

P_ψ :

P_φ :

μ_0 :

PSPACE-hardness: A closer look

Assume $\varphi = \forall x_1 \exists y_1 \, \psi$, where $\psi = (x_1 \vee \neg y_1) \wedge (\neg x_1 \vee y_1)$.

We generate G, P_φ and μ_0 such that μ_0 belongs to the answer of P_φ over G iff φ is valid:

G : $\{(a, \mathtt{tv}, 0),\ (a, \mathtt{tv}, 1),\ (a, \mathtt{false}, 0),\ (a, \mathtt{true}, 1)\}$

R_ψ : $((?X_1 = 1 \vee ?Y_1 = 0)\ \wedge\ (?X_1 = 0 \vee ?Y_1 = 1))$

P_ψ : $(((a, \mathtt{tv}, ?X_1)$ AND $(a, \mathtt{tv}, ?Y_1))$ FILTER $R_\psi)$

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$$P_\psi \quad : \quad (((a, \mathtt{tv}, ?X_1)\ \text{AND}\ (a, \mathtt{tv}, ?Y_1))\ \text{FILTER}\ R_\psi)$$

$$P_\varphi \quad : \quad (a, \mathtt{true}, ?B_0)\ \text{OPT}\ (P_1\ \text{OPT}\ (Q_1\ \text{AND}\ P_\psi))$$

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P_1

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P_1 $\qquad\qquad$ Q_1

$?B_0 \mapsto 1 \longrightarrow ?X_1 \mapsto 0 \longrightarrow ?X_1 \mapsto 0 \quad ?Y_1 \mapsto i \quad ?B_0 \mapsto 0$

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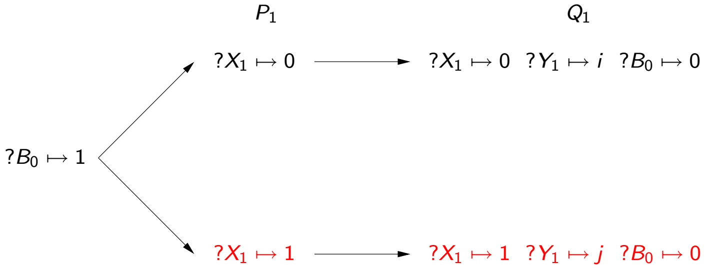

AND-FILTER-OPT fragment: Reducing the complexity

Patterns in the reduction are not very natural:

$$(a, \texttt{true}, ?B_0) \quad \text{OPT} \quad (P_1 \quad \text{OPT} \quad (Q_1 \quad \text{AND} \quad P_\psi))$$

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These patterns rarely occur in practice.

Well–designed patterns

Definition

An AND-FILTER-OPT pattern is well–designed if for every OPT in the pattern:

$$(\cdots\cdots\cdots\cdots \quad (\quad A \quad \mathrm{OPT} \quad B \quad) \quad \cdots\cdots\cdots\cdots)$$

if a variable occurs inside B and anywhere outside the OPT operator, then the variable must also occur inside A.

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Example

$$\Big((?Y, \text{name}, \text{paul}) \text{ OPT } (?X, \text{email}, ?Z) \Big) \quad \text{AND} \quad (?X, \text{name}, \text{john})$$

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AND-FILTER-OPT fragment: Reducing the complexity

Theorem

The evaluation problem is coNP-complete for well-designed AND-FILTER-OPT *patterns.*

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Corollary

The evaluation problem is coNP-complete for patterns of the form P_1 UNION P_2 UNION $\cdots$ UNION P_k, *where each* P_i *is a well-designed* AND-FILTER-OPT *pattern.*

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Can we use this in practice?

- Well-designed patterns are suitable for optimization.

Classical optimization

- Classical optimization assumes null–rejection.
  - null–rejection: the join/outer–join condition must fail in the presence of nulls.
- SPARQL operations are not null–rejecting.
  - by definition of compatible mappings.

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Well–designed graph patterns and optimization

Consider the following rules:

$$
\begin{array}{rcll}
((P_1 \text{ OPT } P_2) \text{ FILTER } R) & \longrightarrow & ((P_1 \text{ FILTER } R) \text{ OPT } P_2) & (1) \\
(P_1 \text{ AND } (P_2 \text{ OPT } P_3)) & \longrightarrow & ((P_1 \text{ AND } P_2) \text{ OPT } P_3) & (2) \\
((P_1 \text{ OPT } P_2) \text{ AND } P_3) & \longrightarrow & ((P_1 \text{ AND } P_3) \text{ OPT } P_2) & (3)
\end{array}
$$

Proposition

If P is a well-designed pattern and Q is obtained from P by applying either (1) or (2) or (3), then Q is a well-designed pattern equivalent to P.

Well–designed graph patterns and optimization

A graph pattern P is in OPT normal form if there exist AND-FILTER patterns Q_1, ..., Q_k such that:

P is constructed from Q_1, ..., Q_k by using only the OPT operator.

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Well–designed graph patterns and optimization

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Patterns in OPT normal form can be evaluated more efficiently:

- AND-FILTER expressions are evaluated first, and then the results are combined using the OPT operator.

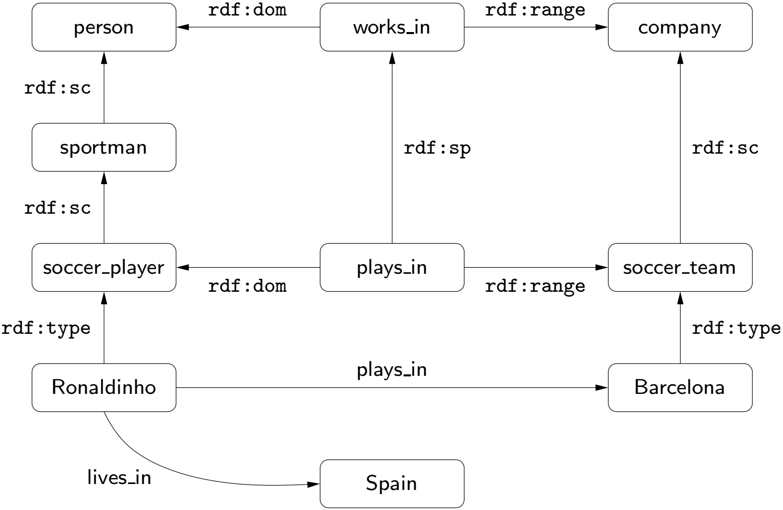
Outline

- RDF and RDFS: A brief introduction
- SPARQL: A query language for RDF
  - Formal semantics
  - Complexity of the evaluation problem
  - Optimization methods
- SPARQL as a query language for RDFS
  - Formal semantics and the closure of an RDFS graph
- NAV-SPARQL: A navigational query language for RDFS

Querying RDFS data

- RDFS extends RDF with a schema vocabulary: subPropertyOf (`rdf:sp`), subClassOf (`rdf:sc`), domain (`rdf:dom`), range (`rdf:range`), type (`rdf:type`).
- Evaluating queries which involve this vocabulary is challenging.
- There is not yet consensus in the Semantic Web community on how to define a query language for RDFS.

A simple SPARQL query: (Ronaldinho, rdf:type, person)



SPARQL over RDFS

Checking whether a triple t is in a graph G is the basic step when answering queries over RDF.

- For the case of RDFS, we need to check whether t is implied by G.

The notion of entailment in RDFS can be defined in terms of classical notions such model, interpretation, etc.

- As for the case of first-order logic.

This notion can also be characterized by a set of inference rules.

Entailment in RDFS

There are inference systems characterizing the notion of entailment in RDFS:

Subproperty rules : $\dfrac{(p, \texttt{rdf:sp}, q) \quad (a, p, b)}{(a, q, b)}$

Subclass rules : $\dfrac{(a, \texttt{rdf:sc}, b) \quad (b, \texttt{rdf:sc}, c)}{(a, \texttt{rdf:sc}, c)}$

Typing rules : $\dfrac{(p, \texttt{rdf:dom}, c) \quad (a, p, b)}{(a, \texttt{rdf:type}, c)}$

...

The closure of an RDFS graph G, denoted by $\mathrm{cl}(G)$, is the graph obtained by adding to G all the triples that are implied by G.

SPARQL over RDFS: Closure of a graph

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The closure of an RDFS graph G, denoted by $\mathrm{cl}(G)$, is the graph obtained by adding to G all the triples that are implied by G.

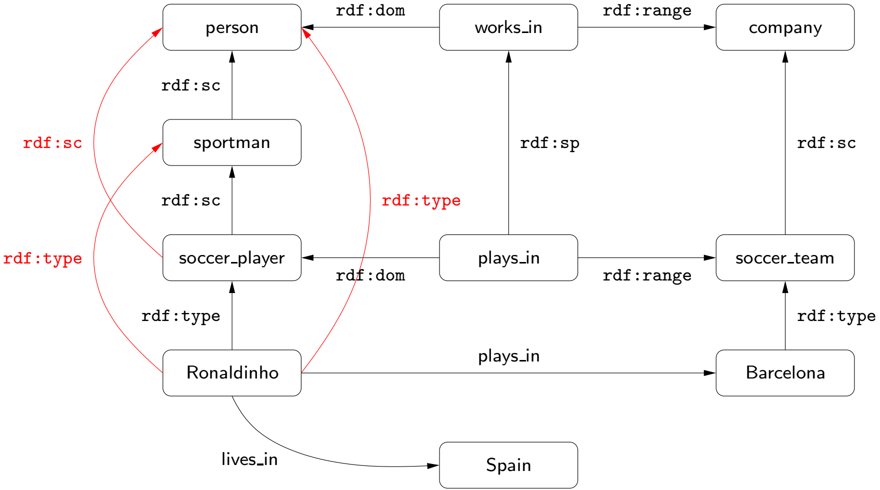
Basic step for answering queries over RDFS:

- Checking whether a tripe t is in $\mathrm{cl}(G)$.

Definition

The *RDFS-evaluation of a graph pattern P over an RDFS graph G* is defined as the evaluation of P over $\mathrm{cl}(G)$.

Example: (Ronaldinho, rdf:type, person) over the closure



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- The size of the closure of G can be quadratic in the size of G.
- Once the closure has been computed, all the queries are evaluated over a graph which can be much larger than the original graph.
- The approach is not goal-oriented.

  When evaluating $(a, \texttt{rdf:sc}, b)$, a goal-oriented approach should not compute $\text{cl}(G)$:

  - It should just verify whether there exists a path from a to b in G where every edge has label `rdf:sc`.

Extending SPARQL with navigational capabilities

The example (a, `rdf:sc`, b) suggests that a query language with navigational capabilities could be appropriate for RDFS.

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This approach has some advantages:

- It is goal-oriented.
- It has been used to design query languages for XML (e.g., XPath and XQuery). The results for these languages can be used here.
- Navigational operators allow to express natural queries that are not expressible in SPARQL over RDFS.

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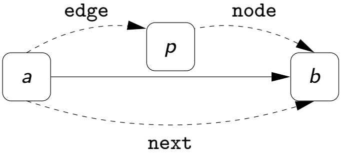
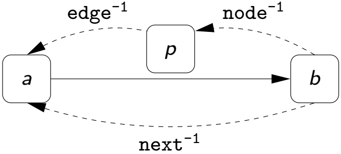
Navigational axes

Forward axes for an RDF triple (a, p, b):



Backward axes for an RDF triple (a, p, b):



A first attempt: 0-NAV-SPARQL

Syntax of navigational expressions:

$$exp \;:=\; \texttt{self} \mid \texttt{self}{::}a \mid \mathsf{axis} \mid \mathsf{axis}{::}a \mid exp/exp \mid exp|exp \mid exp^*$$

where $a \in U$ and $\mathsf{axis} \in \{\texttt{next}, \texttt{next}^{-1}, \texttt{edge}, \texttt{edge}^{-1}, \texttt{node}, \texttt{node}^{-1}\}$.

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Syntax of 0-NAV-SPARQL: SPARQL extended with triples of the form (x, exp, y), where exp is a navigational expression.

- Examples: (Ronaldinho, $\texttt{next::lives\_in}$, Spain) and $(?X, (\texttt{next::(rdf:sc)})^+, ?Y)$.

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Example: $(?X, (\texttt{next::Iberia})^+, ?Y)$ AND $(?X, (\texttt{next::AirFrance})^+, ?Y)$

Is 0-NAV-SPARQL a good language for RDFS?

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- Can we capture SPARQL over RDFS?

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For every RDFS graph G and SPARQL pattern P, we would like to find a 0-NAV-SPARQL pattern Q such that:

- RDFS-evaluation of P over G $=$ evaluation of Q over G.

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Theorem

There is a SPARQL pattern P for which there is no 0-NAV-SPARQL pattern Q such that, for every RDFS graph G:

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- We adopt the notion of branching from XPath.

A successful attempt: NAV-SPARQL

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NAV-SPARQL: Capturing SPARQL over RDFS

Example: $(?X, a, ?Y)$ over RDFS is equivalent to NAV-SPARQL pattern $(?X, \texttt{next}{::}[(\texttt{next}{::}(\texttt{rdf:sp}))^*/(\texttt{self}{::}a)], ?Y)$.

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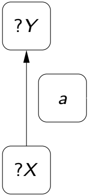

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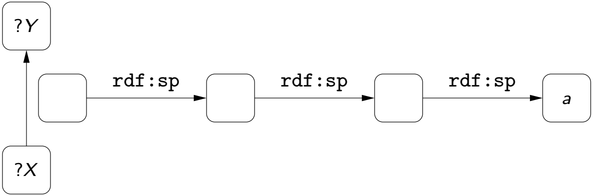

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Proof idea

Replace $(?X, a, ?Y)$ *by* $(?X, R(a), ?Y)$, *where:*

$$\begin{array}{rcl} R(\mathtt{rdf:sc}) & = & (\mathtt{next}::(\mathtt{rdf:sc}))^+ \\ R(\mathtt{rdf:sp}) & = & (\mathtt{next}::(\mathtt{rdf:sp}))^+ \\ & \cdots & \\ R(b) & = & \mathtt{next}::[(\mathtt{next}::(\mathtt{rdf:sp}))^* / (\mathtt{self}::b)] \end{array}$$

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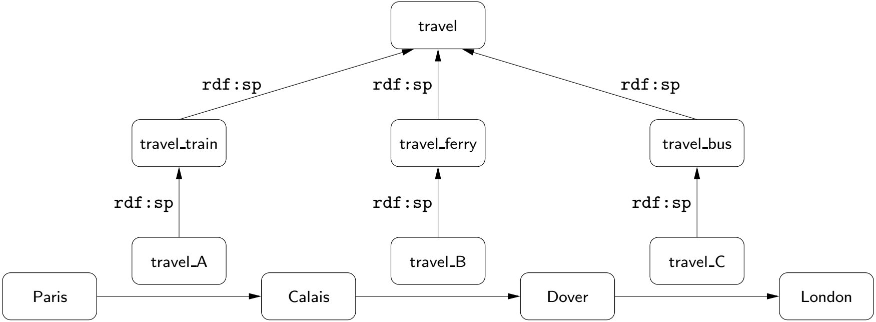
Note: $R(\mathtt{rdf:type})$ *uses* next, edge *and* $\mathtt{node}^{-1}$.

The extra expressive power of NAV-SPARQL



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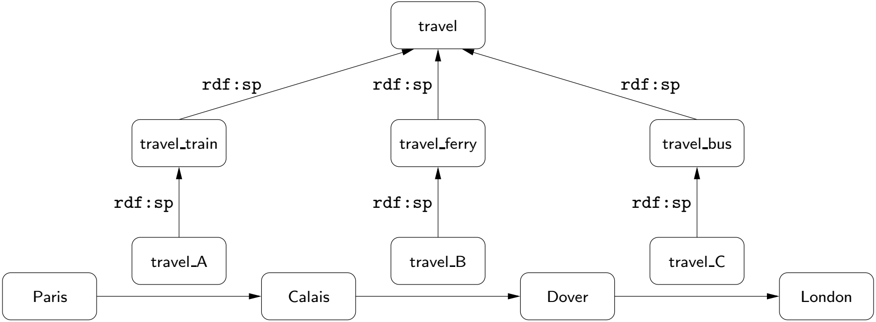

A natural query: $(?X, (\texttt{next}::[(\texttt{next}::(\texttt{rdf:sp}))^*/(\texttt{self}::\text{travel})])^+, ?Y)$

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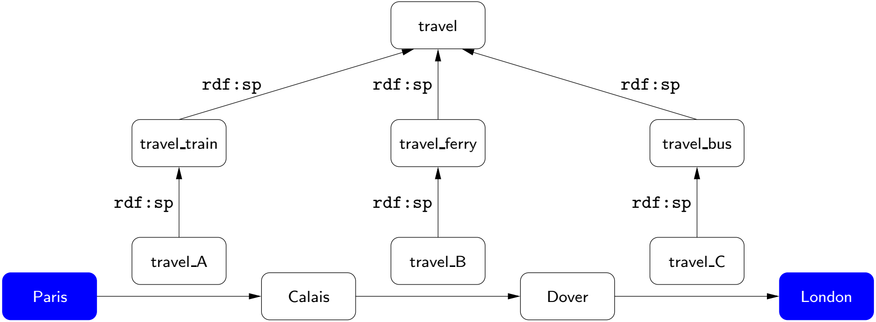

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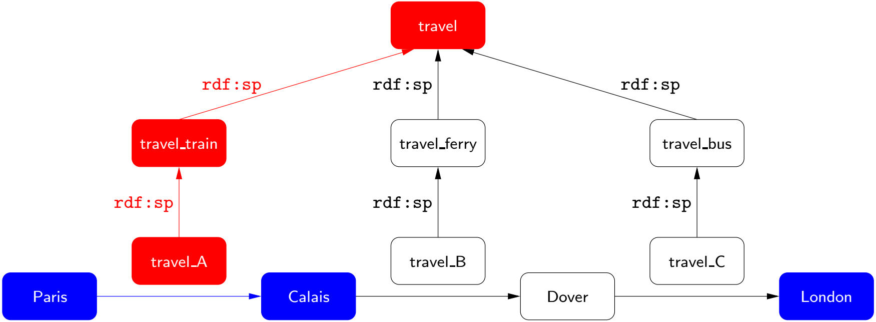

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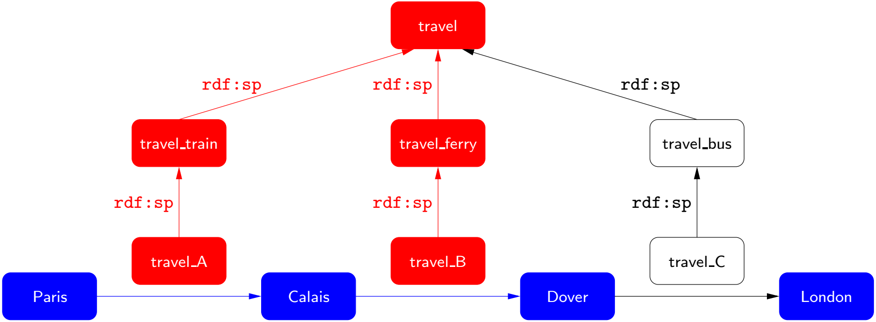

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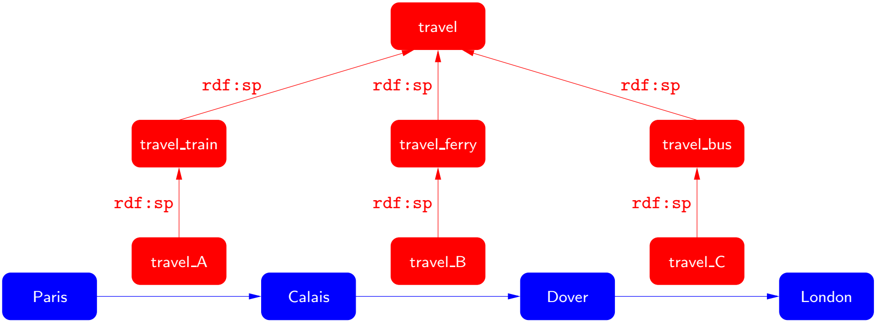

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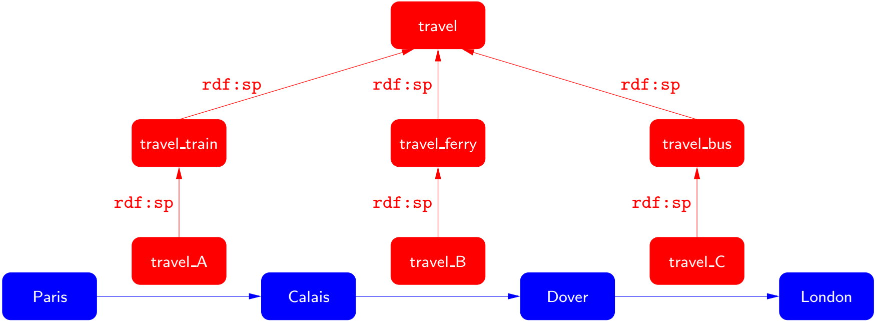

A natural query: $(?X, (\mathtt{next}::[(\mathtt{next}::(\mathtt{rdf:sp}))^*/(\mathtt{self}::\mathrm{travel})])^+, ?Y)$

- This query cannot be expressed in SPARQL over RDFS.

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  - Is there a fragment of NAV-SPARQL which is also appropriate for RDFS? One level of nesting is enough to capture SPARQL over RDFS.