RDF y SPARQL: Dos componentes básicos para la Web de datos

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Semantic Web

"The Semantic Web is an extension of the current web in which information is given well-defined meaning, better enabling computers and people to work in cooperation."

[Tim Berners-Lee et al. 2001.]

Specific goals:

- Build a description language with standard semantics
  - Make semantics machine-processable and understandable
- Incorporate logical infrastructure to reason about resources
- W3C proposals: Resource Description Framework (RDF) and SPARQL

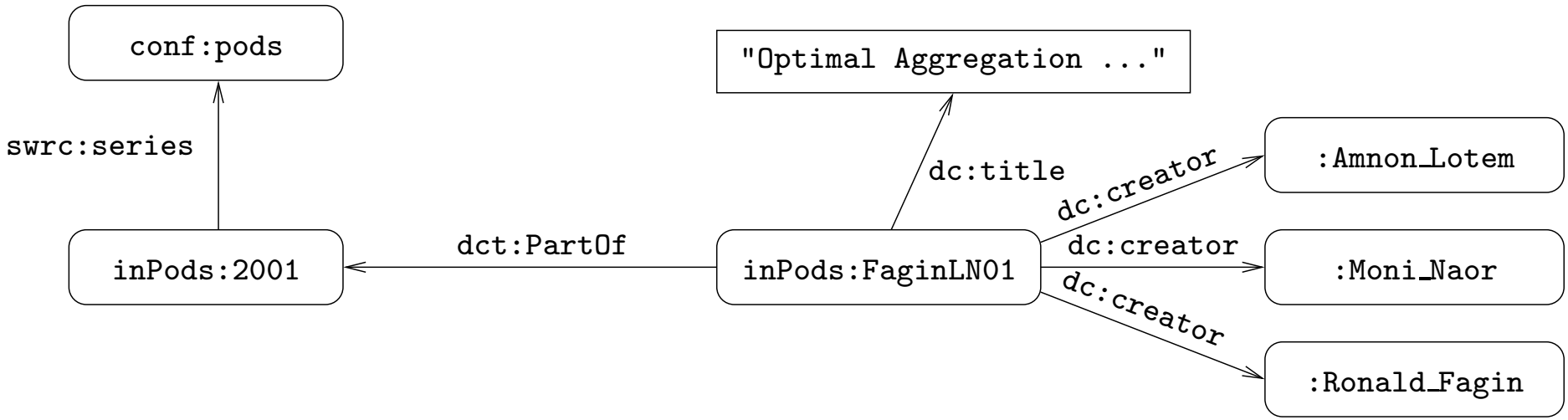
RDF in a nutshell

RDF is the framework proposed by the W3C to represent information in the Web:

- URI vocabulary
  - A URI is an atomic piece of data, and it identifies an abstract resource
- Syntax based on directed labeled graphs
  - URIs are used as node labels and edge labels
- Schema definition language (RDFS): Define new vocabulary
  - Typing, inheritance of classes and properties, ...
- Formal semantics

An example of an RDF graph: DBLP

```
      : <http://dblp.l3s.de/d2r/resource/authors/>
   conf: <http://dblp.l3s.de/d2r/resource/conferences/>
inPods: <http://dblp.l3s.de/d2r/resource/publications/conf/pods/>
   swrc: <http://swrc.ontoware.org/ontology#>
     dc: <http://purl.org/dc/elements/1.1/>
    dct: <http://purl.org/dc/terms/>
```



An example of a URI

`http://dblp.l3s.de/d2r/resource/conferences/pods`

URI can be used for any abstract resource

`http://dblp.l3s.de/d2r/page/authors/Ronald_Fagin`

Querying RDF

Why is this an interesting problem? Why is it challenging?

- RDF graphs can be interconnected
  - URIs should be dereferenceable
- Semantics of RDF is open world
  - RDF graphs are inherently incomplete
  - The possibility of adding optional information if present is an important feature
- Vocabulary with predefined semantics
- ...

Querying RDF: SPARQL

- SPARQL is the W3C recommendation query language for RDF (January 2008).
  - SPARQL is a recursive acronym that stands for *SPARQL Protocol and RDF Query Language*
- SPARQL is a graph-matching query language.
- A SPARQL query consists of three parts:
  - Pattern matching: optional, union, filtering, ...
  - Solution modifiers: projection, distinct, order, limit, offset, ...
  - Output part: construction of new triples, ...

SPARQL in a nutshell

```
SELECT ?Author
WHERE
{
  ?Paper      dc:creator     ?Author .
  ?Paper      dct:PartOf     ?Conf .
  ?Conf       swrc:series    conf:pods .
}
```

SPARQL in a nutshell

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A SPARQL query consists of a:

- Body: Pattern matching expression

SPARQL in a nutshell

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SELECT ?Author
WHERE
{
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  ?Paper      dct:PartOf     ?Conf .
  ?Conf       swrc:series    conf:pods .
}
```

A SPARQL query consists of a:

- Body: Pattern matching expression
- Head: Processing of the variables

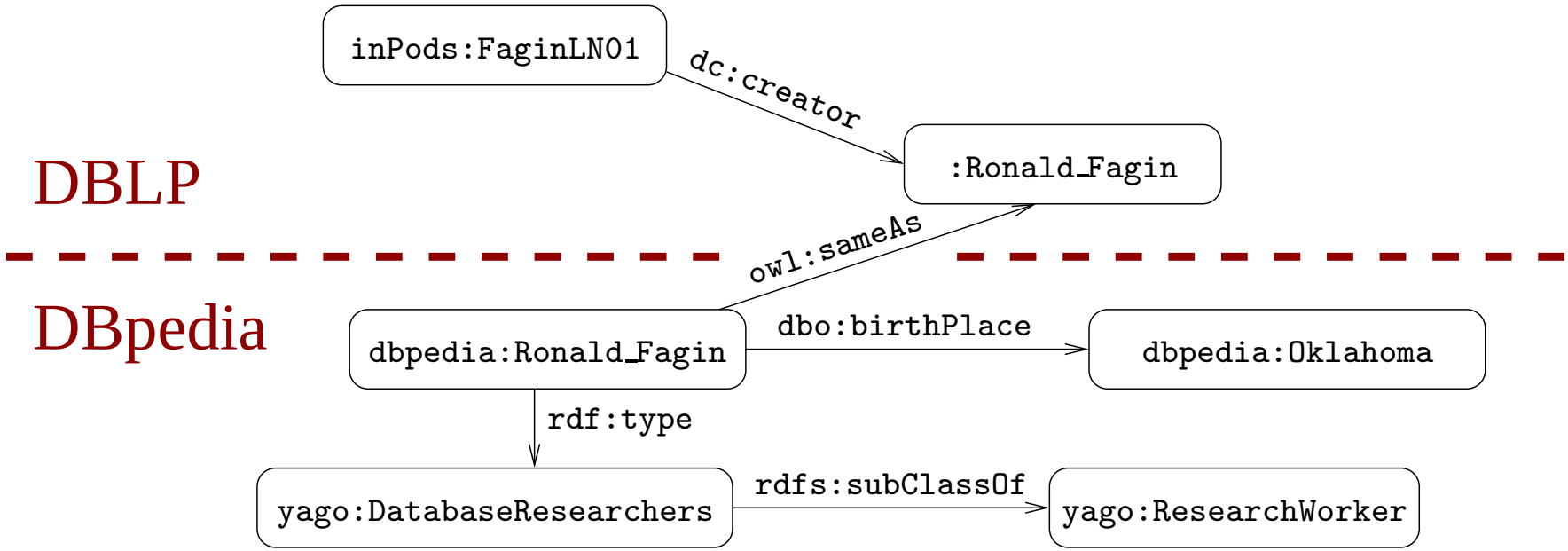
What are the challenges in implementing SPARQL?

SPARQL has to take into account the distinctive features of RDF:

- Should be able to extract information from interconnected RDF graphs
- Should be consistent with the open-world semantics of RDF
  - Should offer the possibility of adding optional information if present
- Should be able to properly interpret RDF graphs with a vocabulary with predefined semantics

Extracting information from interconnected RDF graphs

```
       : <http://dblp.l3s.de/d2r/resource/authors/>
dbpedia: <http://dbpedia.org/resource/>
    rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
   rdfs: <http://www.w3.org/2000/01/rdf-schema#>
    owl: <http://www.w3.org/2002/07/owl#>
   yago: <http://dbpedia.org/class/yago>
    dbo: <http://dbpedia.org/ontology/>
```



Dereferenceable URIs are the glue

`http://dbpedia.org/resource/Ronald_Fagin`

Querying interconnected RDF graphs

Retrieve the authors that have published in PODS and were born in Oklahoma:

```
SELECT ?Author
WHERE
{
  ?Paper      dc:creator      ?Author .
  ?Paper      dct:PartOf      ?Conf .
  ?Conf       swrc:series     conf:pods .
  ?Person     owl:sameAs      ?Author .
  ?Person     dbo:birthPlace dbpedia:Oklahoma .
}
```

Retrieving optional information

Retrieve the authors that have published in PODS, and their Web pages if this information is available:

```
SELECT ?Author ?WebPage
WHERE
{
  ?Paper      dc:creator     ?Author .
  ?Paper      dct:PartOf     ?Conf .
  ?Conf       swrc:series    conf:pods .
  OPTIONAL { ?Author  foaf:homePage  ?WebPage . }
}
```

Taking into account vocabularies with predefined semantics

Retrieve the scientists that were born in Oklahoma and that have published in PODS:

```
SELECT ?Author
WHERE
{
  ?Author     rdf:type        yago:Scientist .
  ?Author     dbo:birthPlace  dbpedia:Oklahoma .
  ?Paper      dc:creator      ?Author .
  ?Paper      dct:PartOf      ?Conf .
  ?Conf       swrc:series     conf:pods .
}
```

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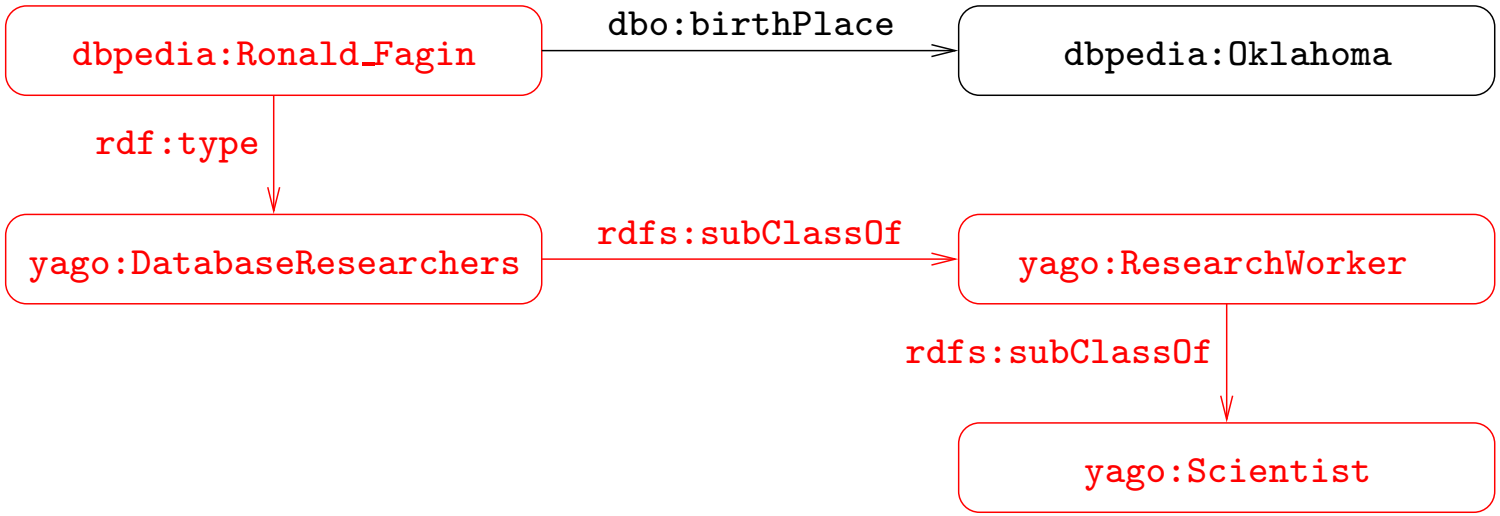

Outline of the talk

- RDF
- SPARQL: Syntax and semantics
- RDFS: RDF Schema
- Some new features in SPARQL 1.1
- Concluding remarks

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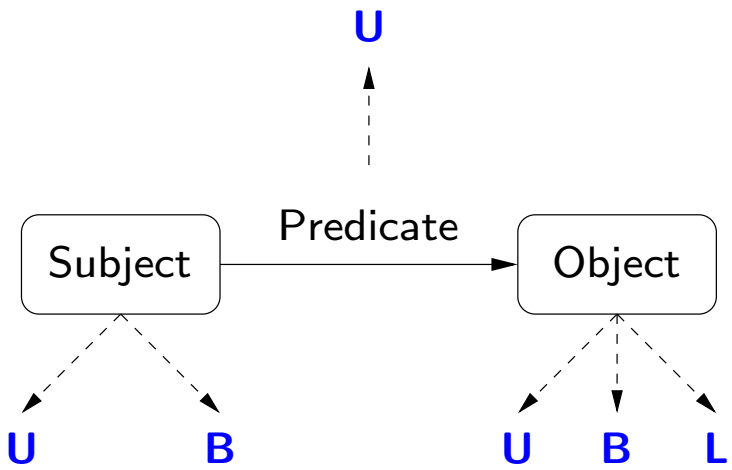
RDF formal model

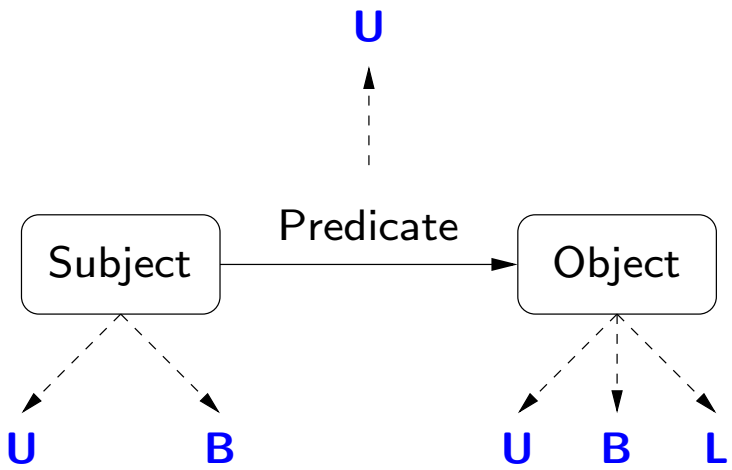


U : set of URIs

B : set of blank nodes

L : set of literals

RDF formal model



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

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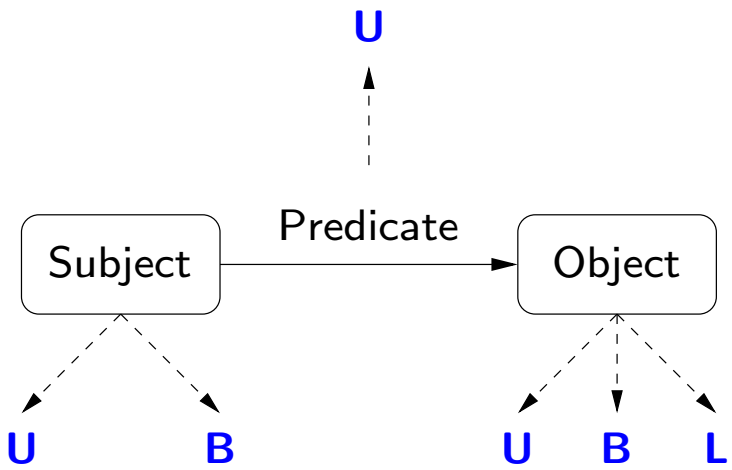

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$(s, p, o) \in (\mathbf{U} \cup \mathbf{B}) \times \mathbf{U} \times (\mathbf{U} \cup \mathbf{B} \cup \mathbf{L})$ is called an RDF triple

A set of RDF triples is called an RDF graph

RDF formal model

Proviso

In this talk, we do not consider blank nodes

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SPARQL queries can be complex

Interesting features:

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

```
{ P1
  P2 }
```

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{ { P1
    P2 }

  { P3
    P4 }

}
```

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```
{ { P1
    P2
    OPTIONAL { P5 }  }

  { P3
    P4
    OPTIONAL { P7 }  }

}
```

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```
{ { P1
    P2
    OPTIONAL { P5 }  }

  { P3
    P4
    OPTIONAL { P7
      OPTIONAL { P8 }  }  }
}
```

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```
{ { P1
    P2
    OPTIONAL { P5 }  }

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

SPARQL queries can be complex

Interesting features:

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

```
{ { P1
    P2
    OPTIONAL { P5 }  }

  { P3
    P4
    OPTIONAL { P7
      OPTIONAL { P8 }  }  }
}
UNION
{ P9
  FILTER ( R ) }
```

SPARQL: An algebraic syntax

- Graph pattern:

`?X name ?Y`	$(?X, \text{name}, ?Y)$
`{ 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 ) }`	$(P_1 \text{ FILTER } R)$

- SPARQL query:

`SELECT ?X ?Y ... { P }`	$(\text{SELECT } \{?X, ?Y, \ldots\} \; P)$

SPARQL: An algebraic syntax (cont'd)

- 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:

$$\mu \quad : \quad \mathbf{V} \longrightarrow (\mathbf{U} \cup \mathbf{L})$$

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

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

The semantics of triple patterns

Given an RDF graph G and a triple pattern t.

Definition

The evaluation of t over G is the set of mappings μ such that:

- μ has as domain the variables in t: $\mathrm{dom}(\mu) = \mathrm{var}(t)$
- μ makes t to match the graph: $\mu(t) \in G$

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Example

graph

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

triple

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

evaluation

	$?X$	$?Y$
μ_1:	R_1	john
μ_2:	R_2	paul

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Example

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

	$?X$	$?Y$
μ_1:	R_1	john
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Compatible mappings

Definition

Mappings μ_1 and μ_2 are compatible if they agree in their common variables:

$$\text{If } ?X \in \text{dom}(\mu_1) \cap \text{dom}(\mu_2), \text{ then } \mu_1(?X) = \mu_2(?X).$$

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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Example

	$?X$	$?Y$	$?Z$	$?V$
μ_1 :	R_1	john		
μ_2 :	R_1		J@edu.ex	
μ_3 :			P@edu.ex	R_2
$\mu_1 \cup \mu_2$:	R_1	john	J@edu.ex	
$\mu_1 \cup \mu_3$:	R_1	john	P@edu.ex	R_2

- μ_2 and μ_3 are not compatible

Sets of mappings and operations

Let Ω_1 and Ω_2 be sets of mappings.

Definition

Join: extends mappings in Ω_1 with compatible mappings in Ω_2

- $\Omega_1 \bowtie \Omega_2 = \{\mu_1 \cup \mu_2 \mid \mu_1 \in \Omega_1,\ \mu_2 \in \Omega_2$ and $\mu_1,\ \mu_2$ are compatible$\}$

Difference: selects mappings in Ω_1 that cannot be extended with mappings in Ω_2

- $\Omega_1 \setminus \Omega_2 = \{\mu_1 \in \Omega_1 \mid$ there is no mapping in Ω_2 compatible with $\mu_1\}$

Sets of mappings and operations

Definition

Union: includes mappings in Ω_1 and in Ω_2

- $\Omega_1 \cup \Omega_2 = \{\mu \mid \mu \in \Omega_1 \text{ or } \mu \in \Omega_2\}$

Left Outer Join: extends mappings in Ω_1 with compatible mappings in Ω_2 **if possible**

- $\Omega_1 \mathbin{⟕} \Omega_2 = (\Omega_1 \bowtie \Omega_2) \cup (\Omega_1 \setminus \Omega_2)$

Semantics of SPARQL

Given an RDF graph G.

Definition

$$[\![t]\!]_G =$$

$$[\![(P_1 \text{ AND } P_2)]\!]_G =$$

$$[\![(P_1 \text{ UNION } P_2)]\!]_G =$$

$$[\![(P_1 \text{ OPT } P_2)]\!]_G =$$

$$[\![(\text{SELECT } W\ P)]\!]_G =$$

Semantics of SPARQL

Given an RDF graph G.

Definition

$$
\begin{aligned}
[\![t]\!]_G &= \{\mu \mid \mathrm{dom}(\mu) = \mathrm{var}(t) \text{ and } \mu(t) \in G\} \\
[\![(P_1 \text{ AND } P_2)]\!]_G &= [\![P_1]\!]_G \bowtie [\![P_2]\!]_G \\
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[\![(P_1 \text{ OPT } P_2)]\!]_G &= [\![P_1]\!]_G \mathbin{⟕} [\![P_2]\!]_G \\
[\![(\text{SELECT } W\ P)]\!]_G &= \{\mu_{|W} \mid \mu \in [\![P]\!]_G\}
\end{aligned}
$$

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Definition

$$
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[\![(P_1 \text{ OPT } P_2)]\!]_G &= [\![P_1]\!]_G \mathbin{⟕} [\![P_2]\!]_G \\
[\![(\text{SELECT } W\ P)]\!]_G &= \{\mu_{|_W} \mid \mu \in [\![P]\!]_G\} \\
& \quad \mathrm{dom}(\mu_{|_W}) = \mathrm{dom}(\mu) \cap W \text{ and} \\
& \quad \mu_{|_W}(?X) = \mu(?X) \text{ for every } ?X \in \mathrm{dom}(\mu_{|_W})
\end{aligned}
$$

Semantics of SPARQL: An example

Example

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

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

Semantics of SPARQL: An example

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

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

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

Semantics of SPARQL: An example

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

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

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

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

Semantics of SPARQL: An example

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$(R_2, \text{name}, \text{paul})$

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

$?X$	$?Y$
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

Semantics of SPARQL: An example

Example

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

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

$?X$	$?Y$
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 Join

Semantics of SPARQL: An example

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- from the Difference

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R_2	paul	

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

- from the Union

Filter expressions (value constraints)

Filter expression: P FILTER R

- P is a graph pattern
- R is a built-in condition

We consider in R:

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

Filter expressions (value constraints)

Example

Some filter expressions:

$$(?X = \texttt{conf:pods})$$

$$\neg(?X = \texttt{conf:pods})$$

$$(?X = \texttt{conf:pods}) \vee (?Y = \texttt{conf:sigmod})$$

$$(?X = \texttt{conf:pods}) \wedge \neg(?Y = \texttt{conf:sigmod})$$

Satisfaction of value constraints

A mapping μ satisfies a condition R ($\mu \models R$) if:

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- R is $?X = c$, $?X \in \text{dom}(\mu)$ and $\mu(?X) = c$
- R is $?X = ?Y$, $?X, ?Y \in \text{dom}(\mu)$ and $\mu(?X) = \mu(?Y)$
- R is bound$(?X)$ and $?X \in \text{dom}(\mu)$

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- R is $(R_1 \vee R_2)$, and $\mu \models R_1$ or $\mu \models R_2$
- R is $(R_1 \wedge R_2)$, $\mu \models R_1$ and $\mu \models R_2$

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Definition

FILTER : selects mappings that satisfy a condition

$$[\![(P \text{ FILTER } R)]\!]_G = \{\mu \in [\![P]\!]_G \mid \mu \models R\}$$

Outline of the talk

- RDF
- SPARQL: Syntax and semantics
- RDFS: RDF Schema
- Some new features in SPARQL 1.1
- Concluding remarks

Syntax of RDFS

RDFS extends RDF with a schema vocabulary: subPropertyOf (`rdf:sp`), subClassOf (`rdf:sc`), domain (`rdf:dom`), range (`rdf:range`), type (`rdf:type`).

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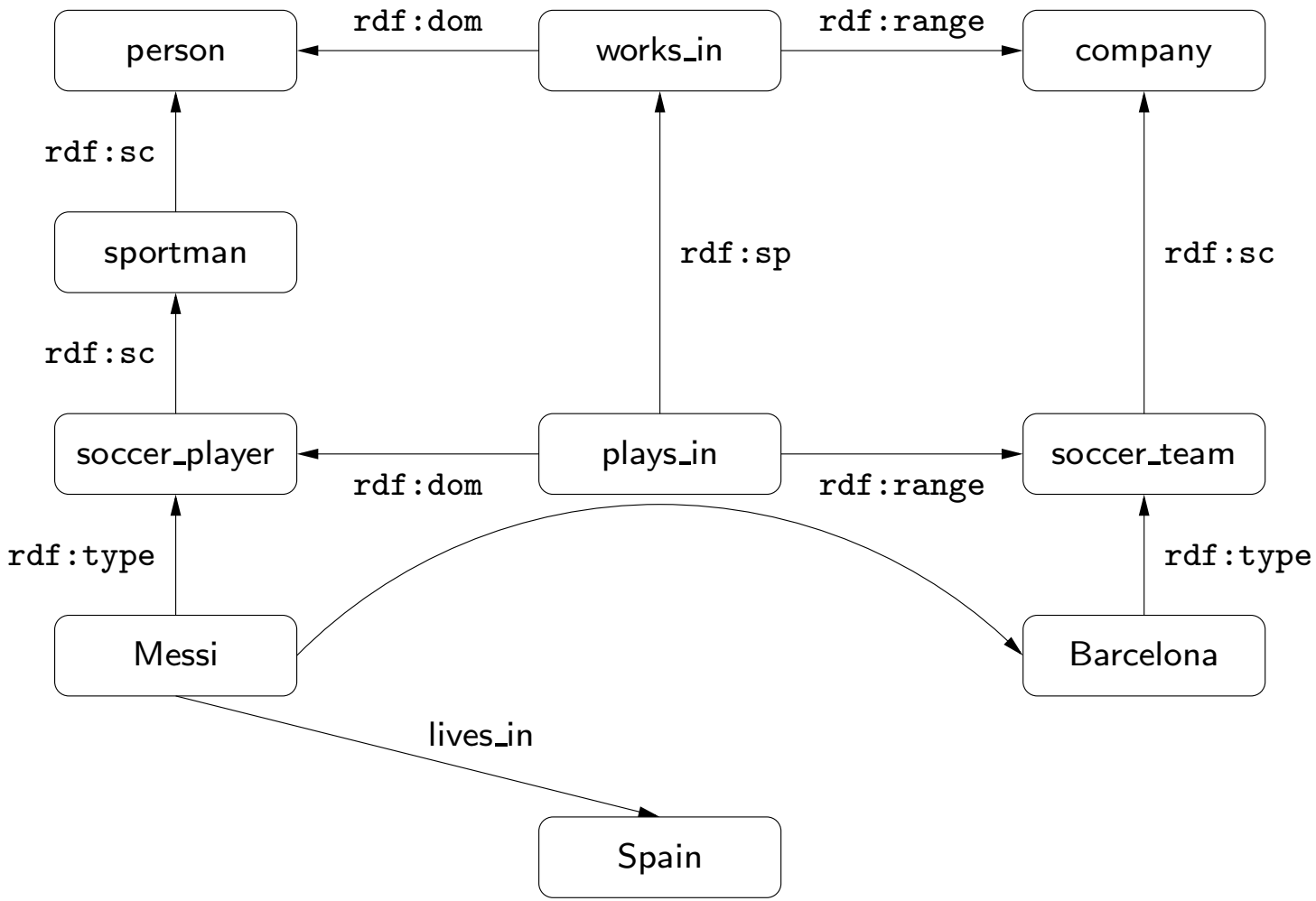
How can one query RDFS data?

- Evaluating queries which involve this vocabulary is challenging

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



Semantics of 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 as model, interpretation, etc.

- As for the case of first-order logic

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

An inference system for RDFS

Inference rule: $\frac{R}{R'}$

- R and R' are sequences of RDF triples including symbols $\mathcal{A}$, $\mathcal{X}$, ..., to be replaced by elements from $(\mathbf{U} \cup \mathbf{L})$

Instantiation of a rule: $\frac{\sigma(R)}{\sigma(R')}$

- $\sigma : \{\mathcal{A}, \mathcal{X}, \ldots\} \to (\mathbf{U} \cup \mathbf{L})$

Application of a rule $\frac{R}{R'}$ to an RDF graph G:

- Select an assignment $\sigma : \{\mathcal{A}, \mathcal{X}, \ldots\} \to (\mathbf{U} \cup \mathbf{L})$
- if $\sigma(R) \subseteq G$, then obtain $G \cup \sigma(R')$

An inference system for RDFS (cont'd)

Sub-property :

$$\frac{(\mathcal{A},\ \texttt{rdf:sp},\ \mathcal{B})\ (\mathcal{B},\ \texttt{rdf:sp},\ \mathcal{C})}{(\mathcal{A},\ \texttt{rdf:sp},\ \mathcal{C})}$$

$$\frac{(\mathcal{A},\ \texttt{rdf:sp},\ \mathcal{B})\ (\mathcal{X},\ \mathcal{A},\ \mathcal{Y})}{(\mathcal{X},\ \mathcal{B},\ \mathcal{Y})}$$

Subclass :

$$\frac{(\mathcal{A},\ \texttt{rdf:sc},\ \mathcal{B})\ (\mathcal{B},\ \texttt{rdf:sc},\ \mathcal{C})}{(\mathcal{A},\ \texttt{rdf:sc},\ \mathcal{C})}$$

$$\frac{(\mathcal{A},\ \texttt{rdf:sc},\ \mathcal{B})\ (\mathcal{X},\ \texttt{rdf:type},\ \mathcal{A})}{(\mathcal{X},\ \texttt{rdf:type},\ \mathcal{B})}$$

Typing :

$$\frac{(\mathcal{A},\ \texttt{rdf:dom},\ \mathcal{B})\ (\mathcal{X},\ \mathcal{A},\ \mathcal{Y})}{(\mathcal{X},\ \texttt{rdf:type},\ \mathcal{B})}$$

$$\frac{(\mathcal{A},\ \texttt{rdf:range},\ \mathcal{B})\ (\mathcal{X},\ \mathcal{A},\ \mathcal{Y})}{(\mathcal{Y},\ \texttt{rdf:type},\ \mathcal{B})}$$

Entailment in RDFS

The previous system of inference rules characterize the notion of entailment in RDFS (without blank nodes).

Thus, a triple t can be deduced from an RDF graph G ($G \models t$) if there exists an RDF G' such that:

- $t \in G'$
- G' can be obtained from G by successively applying the rules in the previous system.

Entailment in RDFS: Closure of a graph

Definition

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

A basic property of the closure:

- $G \models t$ iff $t \in \mathsf{cl}(G)$

Querying RDFS data

Basic step for answering queries over RDFS:

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Basic step for answering queries over RDFS:

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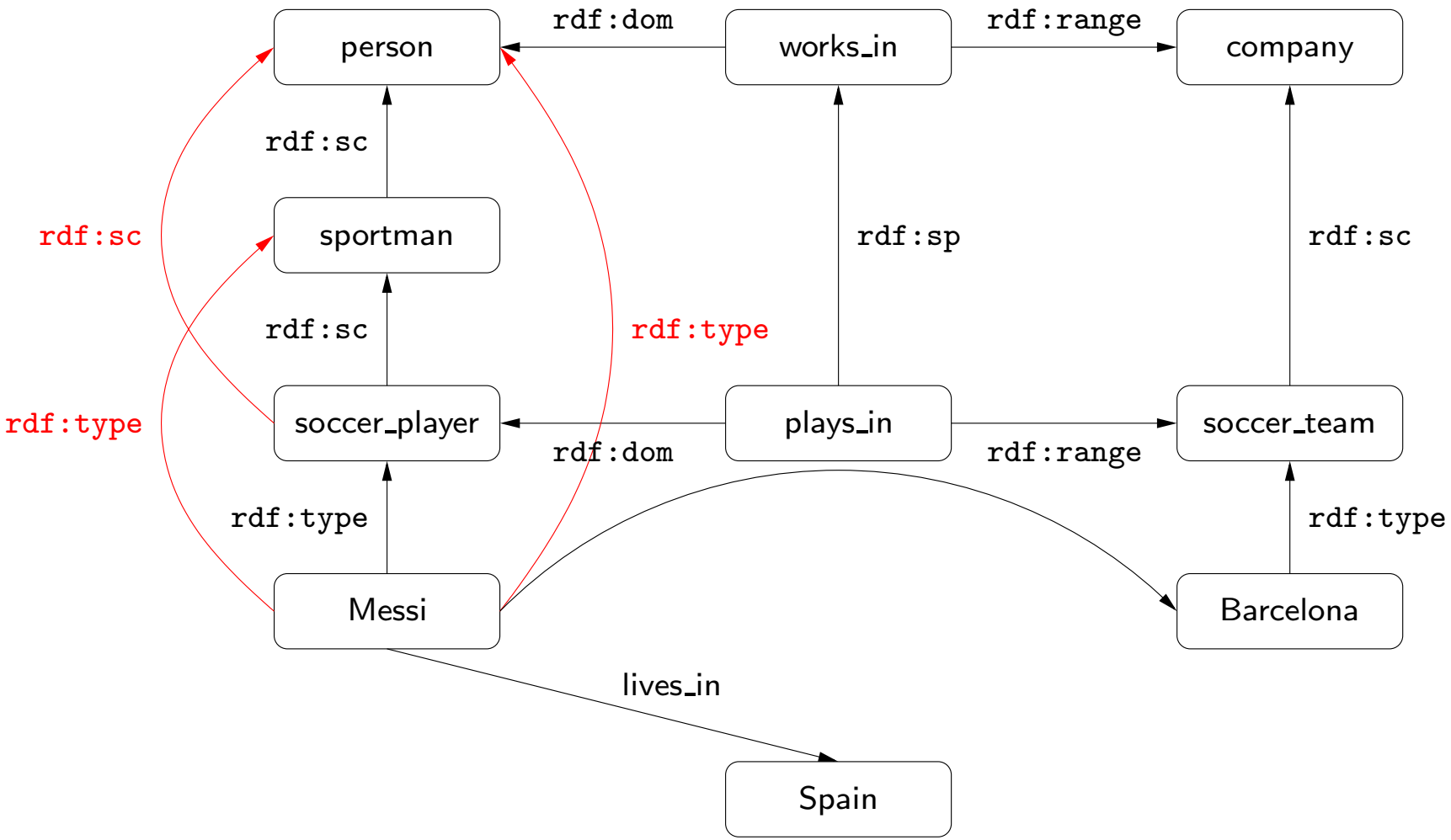
Definition

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

$$[\![P]\!]_G^{\mathrm{rdfs}} \quad = \quad [\![P]\!]_{\mathrm{cl}(G)}$$

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



Answering SPARQL queries over RDFS

A simple approach for answering a SPARQL query P over an RDF graph G:

- Compute $\mathsf{cl}(G)$, and then evaluate P over $\mathsf{cl}(G)$ as for RDF

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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 $\mathsf{cl}(G)$:

  - 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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- 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

Outline of the talk

- RDF
- SPARQL: Syntax and semantics
- RDFS: RDF Schema
- Some new features in SPARQL 1.1
- Concluding remarks

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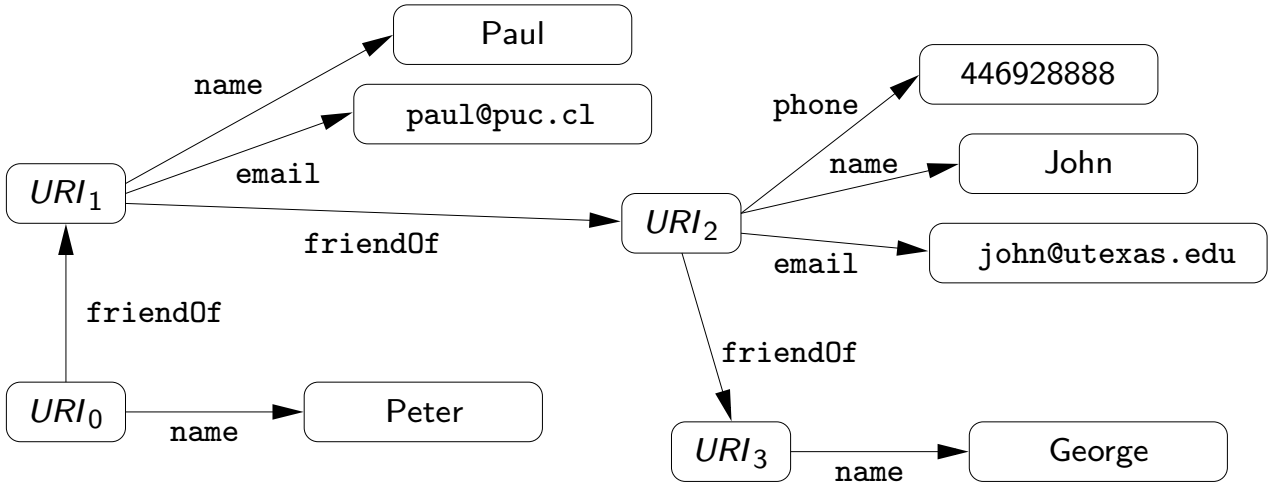
- An operator SERVICE to distribute the execution of a query
  - (SERVICE ?X P)

Aggregates in SPARQL 1.1

```
SELECT COUNT(DISTINCT ?Author)
WHERE
{
  ?Paper      dc:creator     ?Author .
  ?Paper      dct:PartOf     ?Conf .
  ?Conf       swrc:series    conf:pods .
}
```

This query can be executed in the DBLP SPARQL endpoint.

SPARQL provides limited navigational capabilities



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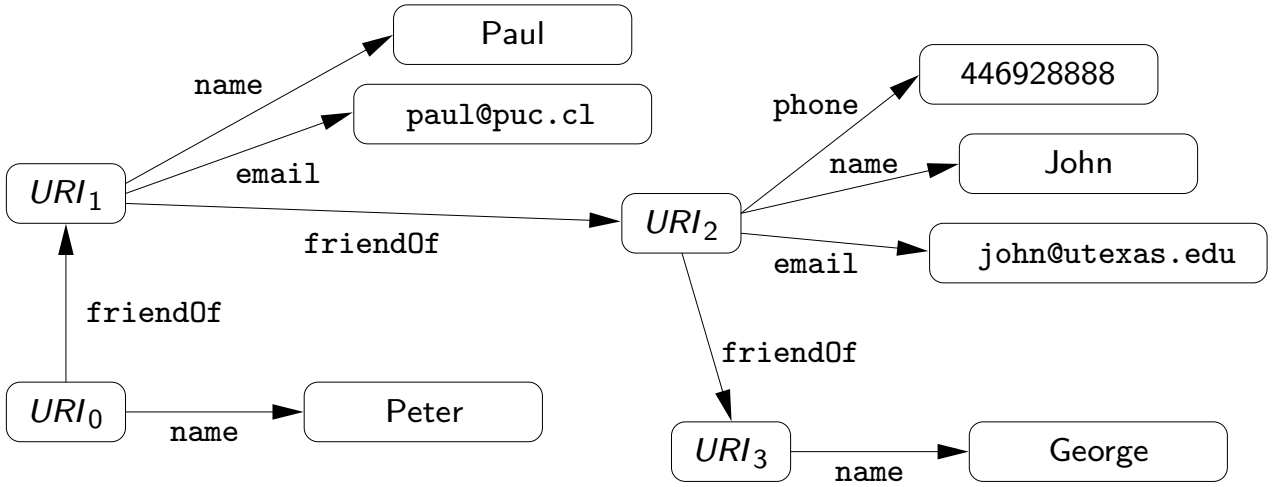

(SELECT ?X ((?X, friendOf, ?Y) AND (?Y, name, George)))

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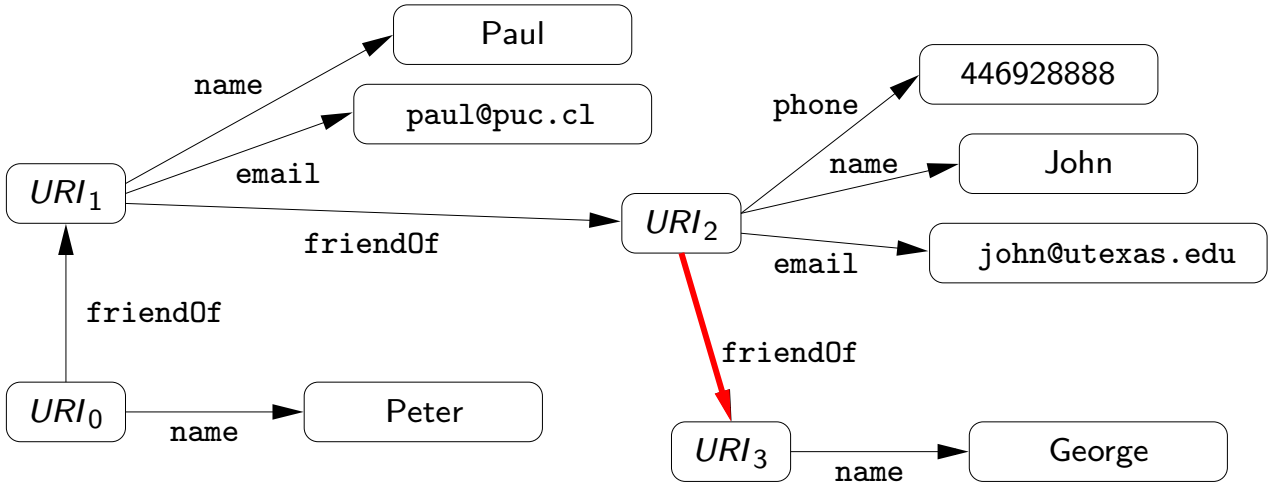

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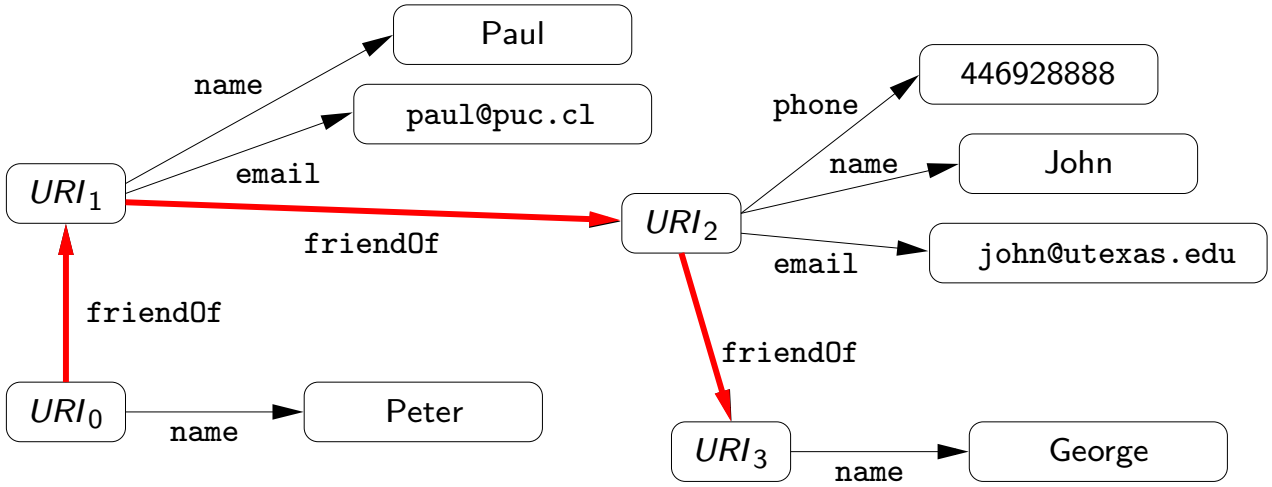

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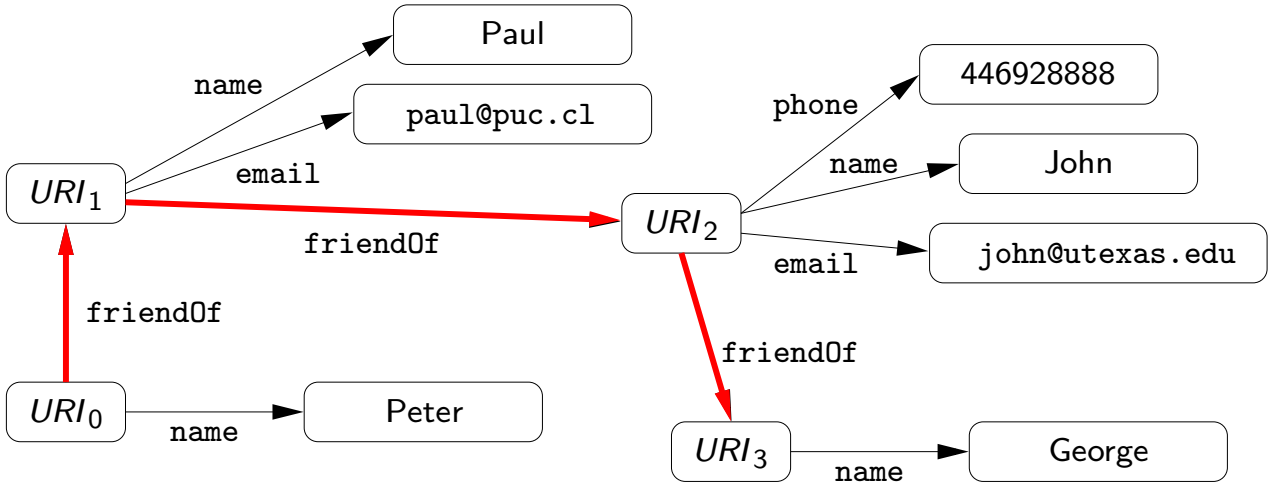
A possible solution: Property paths



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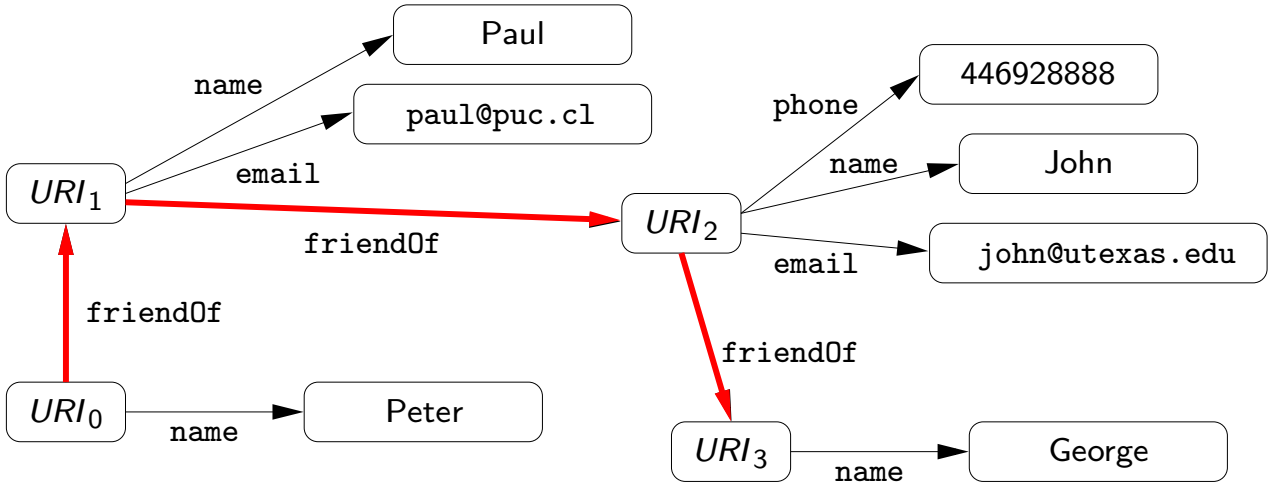

(SELECT ?X ((?X, (friendOf)*, ?Y) AND (?Y, name, George)))

Navigational capabilities in SPARQL 1.1: Property paths

Syntax of property paths:

$$exp \quad := \quad a \;\mid\; exp/exp \;\mid\; exp|exp \;\mid\; exp^*$$

where $a \in \mathbf{U}$

Evaluating property paths

The evaluation of a property path over an RDF graph G is defined as follows:

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[\![exp_1|exp_2]\!]_G &= [\![exp_1]\!]_G \cup [\![exp_2]\!]_G \\
[\![exp^*]\!]_G &= \{(a,a) \mid a \text{ is a URI in } G\} \cup [\![exp]\!]_G \cup [\![exp/exp]\!]_G \cup [\![exp/exp/exp]\!]_G \cup \cdots
\end{aligned}
$$

Property paths in SPARQL 1.1

New element in SPARQL 1.1: A triple of the form (x, exp, y)

- exp is a property path
- x (resp. y) is either an element from **U** or a variable

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Example

- $(?X, (\texttt{rdf:sc})^*, ?Y)$: Verifies whether $?X$ is a subclass of $?Y$
- $(?X, (\texttt{rdf:sp})^*, ?Y)$: Verifies whether $?X$ is a subproperty of $?Y$

Semantics of property paths

Evaluation of $t = (?X, exp, ?Y)$ over an RDF graph G is the set of mappings μ such that:

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Example

- (?X, KLM/(KLM)*, ?Y): It is possible to go from ?X to ?Y by using the airline KLM
- ((?X, KLM/(KLM)*, ?Y) FILTER $\neg(?X = ?Y)$): Same as before, but now ?X, ?Y must be different

SPARQL 1.1 and RDFS

Property paths can help in encoding the semantics of RDFS.

- Given a SPARQL graph pattern P, we would like to find a SPARQL 1.1 graph pattern Q such that:

  For every RDF graph G: $[\![P]\!]_G^{\text{rdfs}} = [\![Q]\!]_G$

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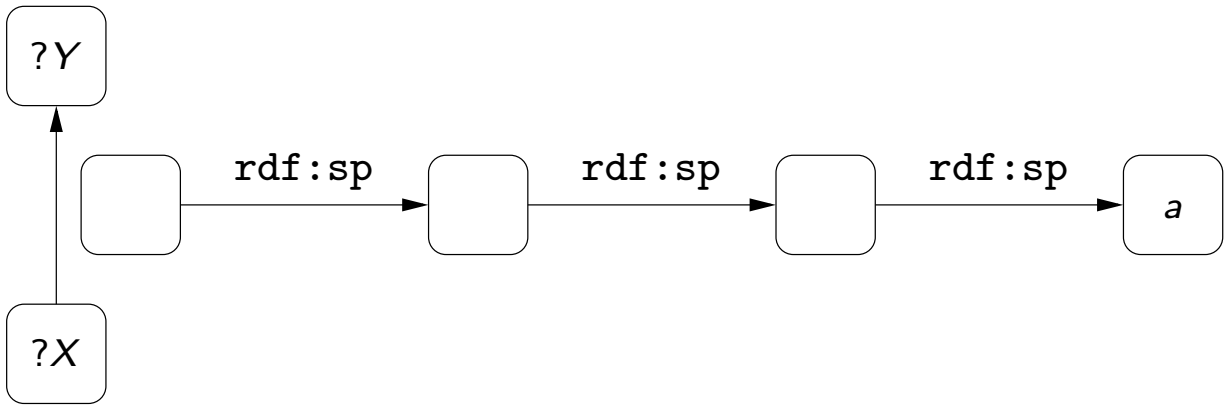
We already saw how to encode `rdf:sc` and `rdf:sp`.

- We will consider the example $P = (?X, a, ?Y)$, where $a \in \mathbf{U} \setminus \{\texttt{rdf:sc}, \texttt{rdf:sp}, \texttt{rdf:type}, \texttt{rdf:dom}, \texttt{rdf:range}\}$

The case of $P = (?X, a, ?Y)$

What are the difficulties in this case?



The case of $P = (?X, a, ?Y)$ (cont'd)

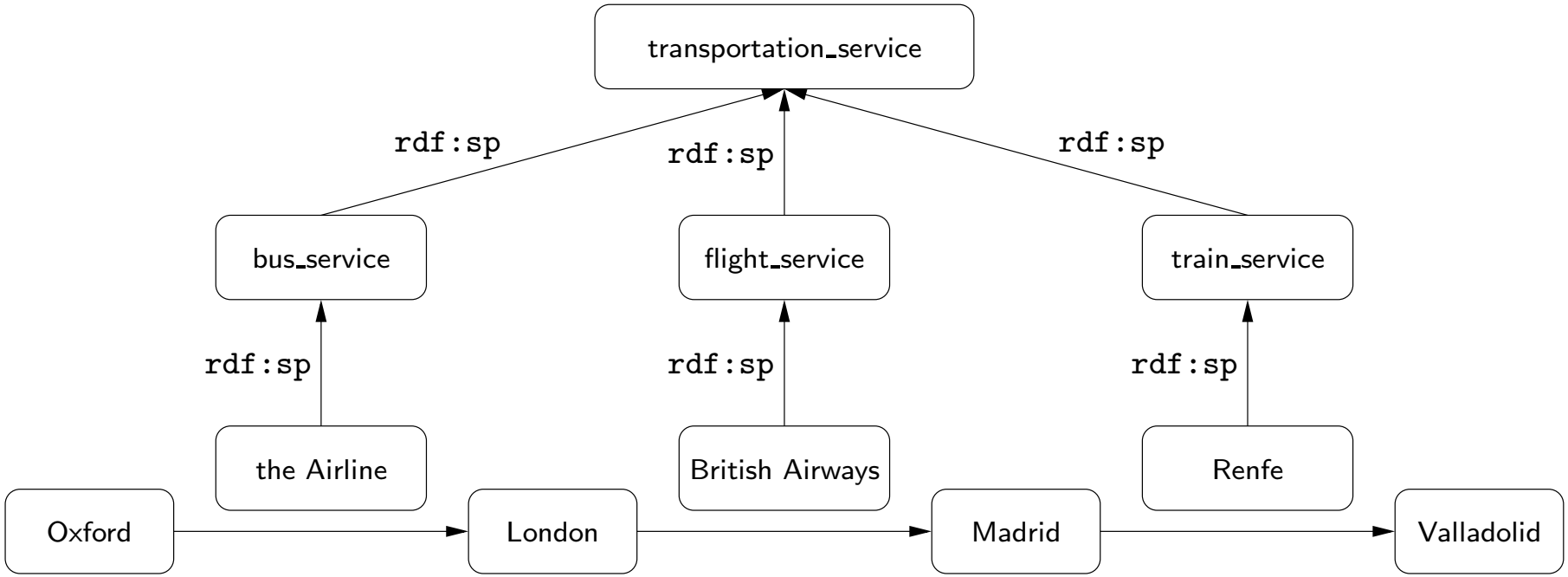
Let Q be:

$$\Big(\text{SELECT } \{?X, ?Y\} \quad ((?X, ?Z, ?Y) \text{ AND } (?Z, (\texttt{rdf:sp})^*, a)) \Big)$$

Then for every RDF graph G: $[\![P]\!]_G^{\text{rdfs}} = [\![Q]\!]_G$

Are we done?

List the pairs a, b of cities such that there is a way to travel from a to b.



Concluding remarks

- We have witnessed a constant growth in the amount of RDF data available on the Web
- Two fundamental components of the Semantic Web: RDF and SPARQL
- Some of the distinctive features of RDF have made the study and implementation of SPARQL challenging
- SPARQL is still under development: SPARQL 1.1, ...

Thank you!