Querying Semantic Web Data with SPARQL

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RDF + SPARQL

MOTIVATION

Relational	Semantic Web
Tables	
SQL	

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Tables	*RDF Graphs*
SQL	

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SQL	*SPARQL*

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Closed Data (inside an organization)	

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Closed Data (inside an organization)	*Open Data* (available on the Web)

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that was born in Chile?

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What is the rainiest place during February?

RDF

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.]

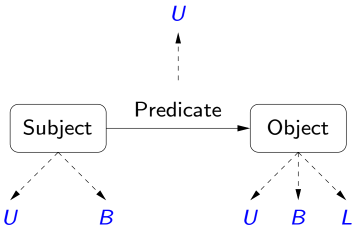
Specific Goals:

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

RDF in a nutshell

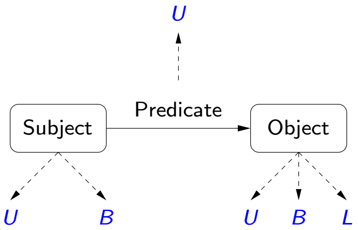
- RDF is the W3C proposal framework for representing information in the Web
- Abstract syntax based on directed labeled graph
- Schema definition language (RDFS): Define new vocabulary (typing, inheritance of classes and properties)
- Extensible URI-based vocabulary
- Formal semantics

RDF formal model



$$
\begin{aligned}
U &= \text{set of Uris} \\
B &= \text{set of Blank nodes} \\
L &= \text{set of Literals}
\end{aligned}
$$

RDF formal model



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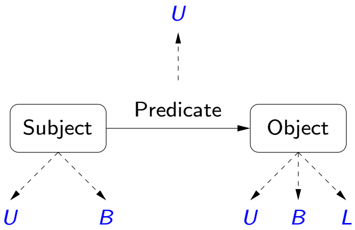

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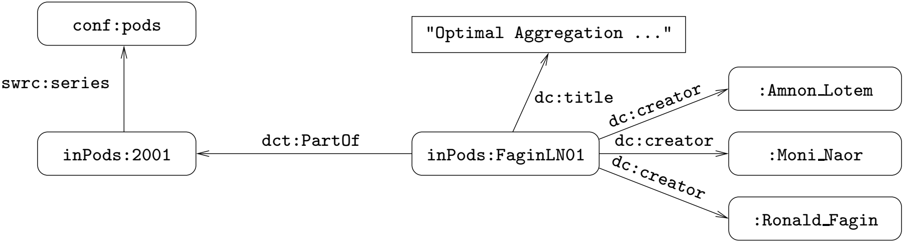
A set of RDF triples is called an RDF graph

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/>
```



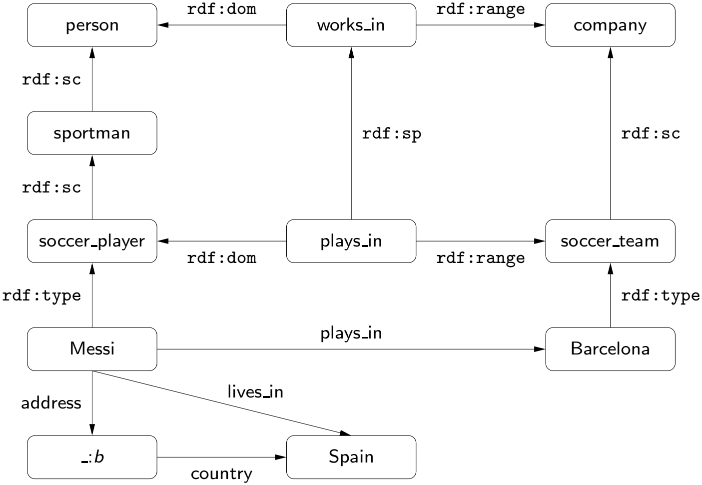
An example of a URI

`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`

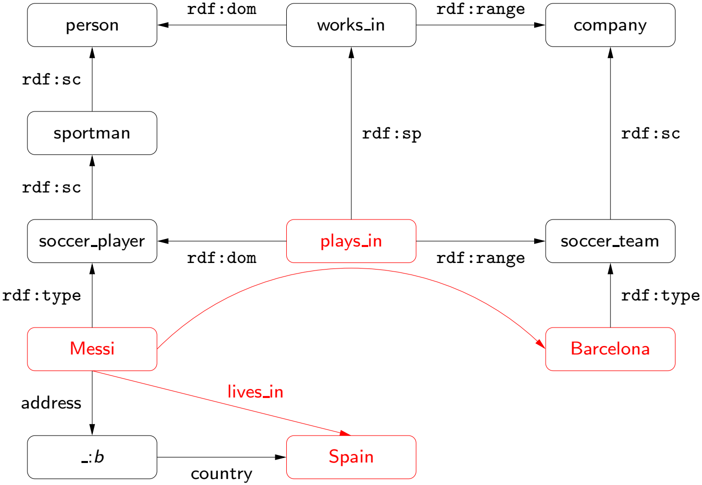
RDF: Another example



Some peculiarities of the RDF data model

- *Existential variables* as datavalues (null values)
- Built-in vocabulary with fixed semantics (RDFS)
- Graph model where nodes may also be edge labels

Previous example: A better representation



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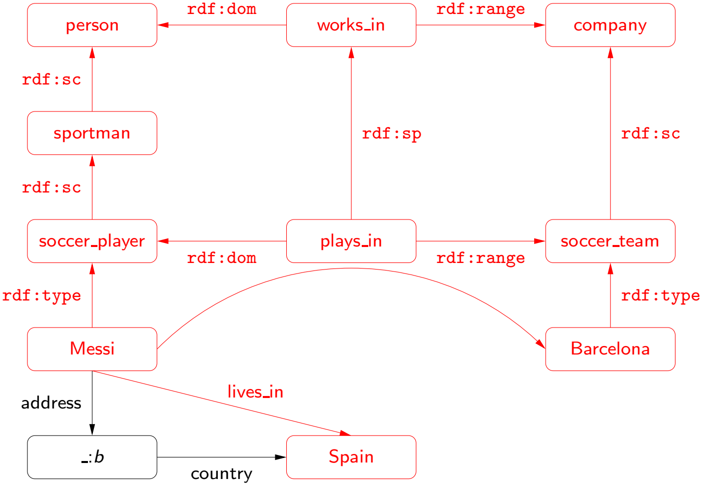

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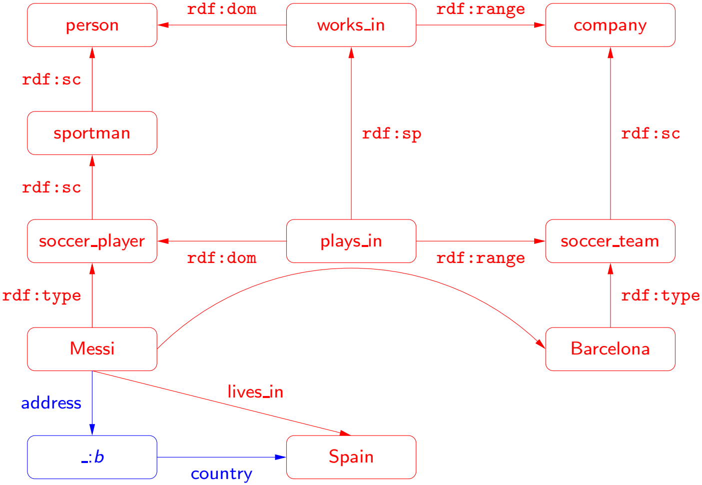
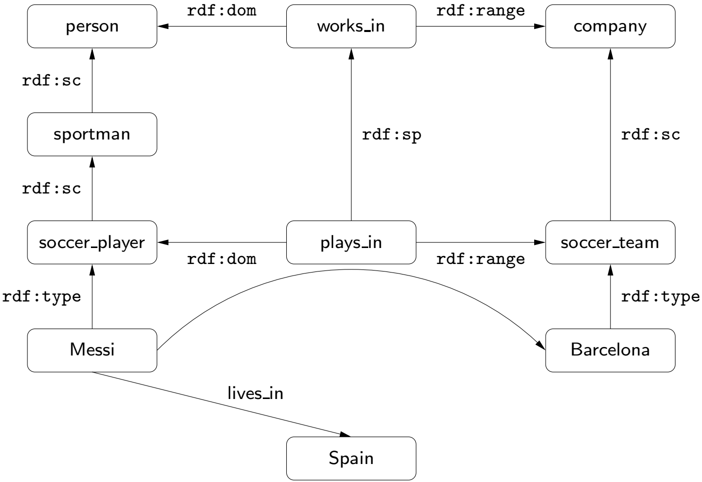


RDF + RDFS

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

plus *semantics* for this vocabulary

RDFS: Messi is a Person



Semantics of RDFS

Checking whether a triple t is in a graph G is the basic step when reasoning about RDF(S).

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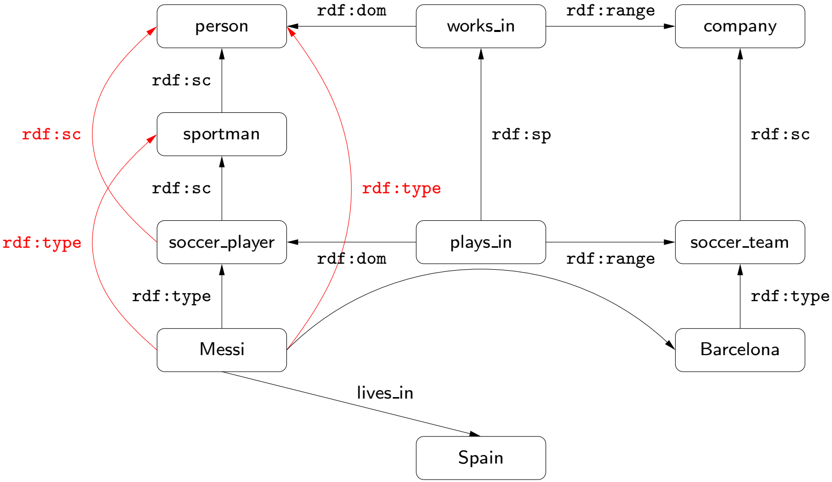
The closure of an RDFS graph G ($\text{cl}(G)$) is the graph obtained by adding to G all the triples that are implied by G.

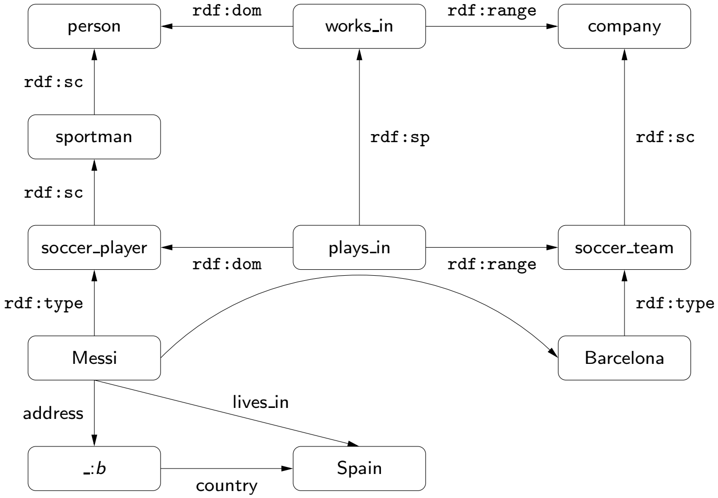
A basic property of the closure:

- G implies t iff $t \in \text{cl}(G)$

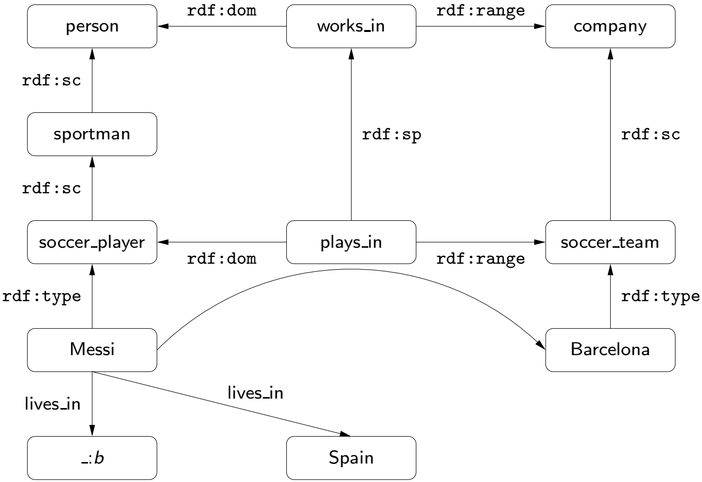
Example: (Messi, rdf:type, person) over the closure



Does the blank node add some information?



What about now?



SPARQL

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: A Simple RDF Query Language

Example: Authors that have published in ISWC

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```
SELECT ?Author
```

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```
SELECT ?Author
WHERE
{



}
```

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Example: Authors that have published in ISWC

```
SELECT ?Author
WHERE
{
  ?Paper      dc:creator     ?Author .


}
```

SPARQL: A Simple RDF Query Language

Example: Authors that have published in ISWC

```
SELECT ?Author
WHERE
{
  ?Paper      dc:creator     ?Author .
  ?Paper      dct:partOf     ?Conf .

}
```

SPARQL: A Simple RDF Query Language

Example: Authors that have published in ISWC

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

SPARQL: A Simple RDF Query Language

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A SPARQL query consists of a:

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A SPARQL query consists of a:

Head: Processing of the variables

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}
```

A SPARQL query consists of a:

Head: Processing of the variables

Body: Pattern matching expression

SPARQL: A Simple RDF Query Language

Example: Authors that have published in ISWC, 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:iswc .

  OPTIONAL {
      ?Author  foaf:homePage  ?WebPage . }
}
```

SPARQL: A Simple RDF Query Language

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But things can become more complex...

Interesting features of pattern matching on graphs

```
SELECT ?X1 ?X2 ...
  { P1 .
    P2 }
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Interesting features of pattern matching on graphs

- Grouping

```
SELECT ?X1 ?X2 ...
 {{ P1 .
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  { P3 .
    P4 }


 }
```

But things can become more complex...

Interesting features of pattern matching on graphs

- Grouping
- Optional parts

```
SELECT ?X1 ?X2 ...
 {{ P1 .
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    OPTIONAL { P5 }  }

  { P3 .
    P4
    OPTIONAL { P7 }  }

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```

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Interesting features of pattern matching on graphs

- Grouping
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- Union of patterns

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 UNION
 { P9 }}
```

But things can become more complex...

Interesting features of pattern matching on graphs

- Grouping
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- Union of patterns
- Filtering

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SELECT ?X1 ?X2 ...
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What is the (formal) *meaning* of a general SPARQL query?

SPARQL: An algebraic syntax

V: set of variables

Each variable is assumed to start with ?

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Basic graph pattern (bgp): Finite set of triple patterns

Examples: $\{(?X, \text{knows}, ?Y), (?Y, \text{name}, \text{john})\}$

SPARQL: An algebraic syntax (cont'd)

Recursive definition of SPARQL graph patterns:

- Every basic graph pattern is a graph pattern
- If P_1, P_2 are graph patterns, then $(P_1 \text{ AND } P_2)$, $(P_1 \text{ OPT } P_2)$, $(P_1 \text{ UNION } P_2)$ are graph pattern
- If P is a graph pattern and R is a *built-in condition*, then $(P \text{ FILTER } R)$ is a graph pattern

SPARQL query:

- If P is a graph pattern and W is a finite set of variables, then $(\text{SELECT } \ W \ P)$ is a SPARQL query

Standard versus algebraic notation

```
?X :name "john"
```

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

Standard versus algebraic notation

```
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```

(?X, name, john)

```
{  P1  .  P2  }
```

(P_1 AND P_2)

Standard versus algebraic notation

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`{  P1 .  P2  }`	$(\, P_1 \text{ AND } P_2 \,)$
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`{ P1 FILTER ( R ) }`	$(P_1 \text{ FILTER } R)$

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`{  P1 FILTER ( R ) }`	$(\,P_1 \text{ FILTER } R\,)$
`SELECT  W  WHERE { P }`	$(\text{SELECT } \; W \; P\,)$

Mappings: building block for the semantics

Definition

A mapping is a partial function:

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$$\mu = \{?X \to R_1, ?Y \to R_2, ?Z \to \text{john}\}$$

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$$\mu(t) = (R_1, \text{name}, \text{john})$$

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- $\mu(t) \in G$

Example

$$G$$

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

$$[\![(?X, \text{name}, ?N)]\!]_G$$

Example

G

$(R_1$, name, john$)$

$(R_1$, email, J@ed.ex$)$

$(R_2$, name, paul$)$

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$$\left\{ \begin{array}{l} \mu_1 = \{?X \to R_1, ?N \to \text{john}\} \\ \mu_2 = \{?X \to R_2, ?N \to \text{paul}\} \end{array} \right\}$$

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$$[\![(?X, \text{name}, ?N)]\!]_G$$

	$?X$	$?N$
μ_1	R_1	john
μ_2	R_2	paul

$$[\![(?X, \text{email}, ?E)]\!]_G$$

	$?X$	$?E$
μ	R_1	J@ed.ex

Example

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

$[\![(R_1, \text{webPage}, ?W)]\!]_G$

$[\![(R_3, \text{name}, \text{ringo})]\!]_G$

$[\![(R_2, \text{name}, \text{paul})]\!]_G$

Example

$$G$$

$$(R_1,\ \text{name},\ \text{john})$$
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$$\{\ \ \}$$

$$[\![(R_2, \text{name}, \text{paul})]\!]_G$$
$$\{\ \mu_\emptyset = \{\ \}\ \}$$

Semantics of SPARQL: Basic graph patterns

Let P be a basic graph pattern

- $\text{var}(P)$: set of variables mentioned in P

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Let P be a basic graph pattern

- var(P): set of variables mentioned in P

Given a mapping μ such that var(P) $\subseteq$ dom(μ):

$$\mu(P) \;=\; \{\mu(t) \mid t \in P\}$$

Semantics of SPARQL: Basic graph patterns

Let P be a basic graph pattern

- var(P): set of variables mentioned in P

Given a mapping μ such that $\text{var}(P) \subseteq \text{dom}(\mu)$:

$$\mu(P) \;=\; \{\mu(t) \mid t \in P\}$$

Definition

The evaluation of P over an RDF graph G, denoted by $[\![P]\!]_G$, is the set of mappings μ:

- $\text{dom}(\mu) = \text{var}(P)$
- $\mu(P) \subseteq G$

Semantics of basic graph patterns: An example

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

Semantics of basic graph patterns: An example

graph	bgp	evaluation
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graph	bgp	evaluation
$(R_1$, name, john$)$ $(R_1$, email, J@ed.ex$)$ $(R_2$, name, paul$)$	$\{(?X$, name, $?Y)$, $(?X$, email, $?Z)\}$	μ:

$?X$	$?Y$	$?Z$
R_1	john	J@ed.ex

Semantics of basic graph patterns: An example

graph	bgp	evaluation
$(R_1$, name, john$)$ $(R_1$, email, J@ed.ex$)$ $(R_2$, name, paul$)$	$\{(?X$, name, $?Y),$ $(?X$, email, $?Z)\}$	μ:

$?X$	$?Y$	$?Z$
R_1	john	J@ed.ex

Notation

t is used to represent $\{t\}$

Compatible mappings: mappings that can be merged

Definition

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

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

Compatible mappings: mappings that can be merged

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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

Compatible mappings: mappings that can be merged

Definition

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

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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	

Compatible mappings: mappings that can be merged

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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	

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$\mu_1 \cup \mu_2$:	R_1	john	J@edu.ex	
$\mu_1 \cup \mu_3$:	R_1	john	P@edu.ex	R_2

Compatible mappings: mappings that can be merged

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
$\mu_1 \cup \mu_2$:	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: $\Omega_1 \bowtie \Omega_2$

- $\{\mu_1 \cup \mu_2 \mid \mu_1 \in \Omega_1, \mu_2 \in \Omega_2,$ and μ_1, μ_2 are compatibles$\}$
- extending mappings in Ω_1 with compatible mappings in Ω_2

will be used to define AND

Sets of mappings and operations

Let Ω_1 and Ω_2 be sets of mappings:

Definition

Join: $\Omega_1 \bowtie \Omega_2$

- $\{\mu_1 \cup \mu_2 \mid \mu_1 \in \Omega_1, \mu_2 \in \Omega_2,$ and μ_1, μ_2 are compatibles$\}$
- extending mappings in Ω_1 with compatible mappings in Ω_2

will be used to define AND

Definition

Union: $\Omega_1 \cup \Omega_2$

- $\{\mu \mid \mu \in \Omega_1$ or $\mu \in \Omega_2\}$
- mappings in Ω_1 plus mappings in Ω_2 (the usual union of sets)

will be used to define UNION

Sets of mappings and operations

Definition

Difference: $\Omega_1 \setminus \Omega_2$

- $\{\mu \in \Omega_1 \mid$ for all $\mu' \in \Omega_2$, μ and μ' are not compatibles$\}$
- mappings in Ω_1 that cannot be extended with mappings in Ω_2

Sets of mappings and operations

Definition

Difference: $\Omega_1 \smallsetminus \Omega_2$

- $\{\mu \in \Omega_1 \mid$ for all $\mu' \in \Omega_2$, μ and μ' are not compatibles$\}$
- mappings in Ω_1 that cannot be extended with mappings in Ω_2

Definition

Left outer join: $\Omega_1 ⟕ \Omega_2 = (\Omega_1 \bowtie \Omega_2) \cup (\Omega_1 \smallsetminus \Omega_2)$

- extension of mappings in Ω_1 with compatible mappings in Ω_2
- plus the mappings in Ω_1 that cannot be extended.

will be used to define OPT

Semantics of SPARQL: AND, UNION, OPT and SELECT

Given an RDF graph G

Definition

$$
\begin{aligned}
[\![(P_1 \text{ AND } P_2)]\!]_G &= \\
[\![(P_1 \text{ UNION } P_2)]\!]_G &= \\
[\![(P_1 \text{ OPT } P_2)]\!]_G &= \\
[\![(\text{SELECT } W\ P)]\!]_G &=
\end{aligned}
$$

Semantics of SPARQL: AND, UNION, OPT and SELECT

Given an RDF graph G

Definition

$$
\begin{aligned}
[\![(P_1 \text{ AND } P_2)]\!]_G &= [\![P_1]\!]_G \bowtie [\![P_2]\!]_G \\
[\![(P_1 \text{ UNION } P_2)]\!]_G &= [\![P_1]\!]_G \cup [\![P_2]\!]_G \\
[\![(P_1 \text{ OPT } P_2)]\!]_G &= [\![P_1]\!]_G ⟕ [\![P_2]\!]_G \\
[\![(\text{SELECT } W \; P)]\!]_G &= \{\mu_{|W} \mid \mu \in [\![P]\!]_G\}
\end{aligned}
$$

Semantics of SPARQL: AND, UNION, OPT and SELECT

Given an RDF graph G

Definition

$$
\begin{aligned}
[\![(P_1 \text{ AND } P_2)]\!]_G &= [\![P_1]\!]_G \bowtie [\![P_2]\!]_G \\
[\![(P_1 \text{ UNION } P_2)]\!]_G &= [\![P_1]\!]_G \cup [\![P_2]\!]_G \\
[\![(P_1 \text{ OPT } P_2)]\!]_G &= [\![P_1]\!]_G \mathbin{⟕} [\![P_2]\!]_G \\
[\![(\text{SELECT } W \ P)]\!]_G &= \{\mu_{|W} \mid \mu \in [\![P]\!]_G\}
\end{aligned}
$$

$\text{dom}(\mu_{|W}) = \text{dom}(\mu) \cap W$ and

$\mu_{|W}(?X) = \mu(?X)$ for every $?X \in \text{dom}(\mu_{|W})$

Example (AND)

$$G: \begin{array}{lll} (R_1,\ \text{name},\ \text{john}) & (R_2,\ \text{name},\ \text{paul}) & (R_3,\ \text{name},\ \text{ringo}) \\ (R_1,\ \text{email},\ \text{J@ed.ex}) & & (R_3,\ \text{email},\ \text{R@ed.ex}) \\ & & (R_3,\ \text{webPage},\ \text{www.ringo.com}) \end{array}$$

$$[\![((?X,\ \text{name},\ ?N)\ \text{AND}\ (?X,\ \text{email},\ ?E))]\!]_G$$

Example (AND)

$$G: \begin{array}{lll} (R_1, \text{name}, \text{john}) & (R_2, \text{name}, \text{paul}) & (R_3, \text{name}, \text{ringo}) \\ (R_1, \text{email}, \text{J@ed.ex}) & & (R_3, \text{email}, \text{R@ed.ex}) \\ & & (R_3, \text{webPage}, \text{www.ringo.com}) \end{array}$$

$$[\![((?X, \text{name}, ?N) \text{ AND } (?X, \text{email}, ?E))]\!]_G$$

$$[\![(?X, \text{name}, ?N)]\!]_G \bowtie [\![(?X, \text{email}, ?E)]\!]_G$$

Example (AND)

G : $(R_1, \text{name}, \text{john})$ $(R_2, \text{name}, \text{paul})$ $(R_3, \text{name}, \text{ringo})$
$(R_1, \text{email}, \text{J@ed.ex})$ $(R_3, \text{email}, \text{R@ed.ex})$
$(R_3, \text{webPage}, \text{www.ringo.com})$

$$[\![((?X, \text{name}, ?N) \text{ AND } (?X, \text{email}, ?E))]\!]_G$$

$$[\![(?X, \text{name}, ?N)]\!]_G \bowtie [\![(?X, \text{email}, ?E)]\!]_G$$

	$?X$	$?N$
μ_1	R_1	john
μ_2	R_2	paul
μ_3	R_3	ringo

Example (AND)

$$G : \begin{array}{lll} (R_1, \text{name}, \text{john}) & (R_2, \text{name}, \text{paul}) & (R_3, \text{name}, \text{ringo}) \\ (R_1, \text{email}, \text{J@ed.ex}) & & (R_3, \text{email}, \text{R@ed.ex}) \\ & & (R_3, \text{webPage}, \text{www.ringo.com}) \end{array}$$

$$[\![((?X, \text{name}, ?N) \text{ AND } (?X, \text{email}, ?E))]\!]_G$$

$$[\![(?X, \text{name}, ?N)]\!]_G \bowtie [\![(?X, \text{email}, ?E)]\!]_G$$

	?X	?N
μ_1	R_1	john
μ_2	R_2	paul
μ_3	R_3	ringo

	?X	?E
μ_4	R_1	J@ed.ex
μ_5	R_3	R@ed.ex

Example (AND)

$$G: \begin{array}{lll} (R_1,\ \text{name},\ \text{john}) & (R_2,\ \text{name},\ \text{paul}) & (R_3,\ \text{name},\ \text{ringo}) \\ (R_1,\ \text{email},\ \text{J@ed.ex}) & & (R_3,\ \text{email},\ \text{R@ed.ex}) \\ & & (R_3,\ \text{webPage},\ \text{www.ringo.com}) \end{array}$$

$$[\![((?X,\ \text{name},\ ?N)\ \text{AND}\ (?X,\ \text{email},\ ?E))]\!]_G$$

$$[\![(?X,\ \text{name},\ ?N)]\!]_G \bowtie [\![(?X,\ \text{email},\ ?E)]\!]_G$$

	$?X$	$?N$
μ_1	R_1	john
μ_2	R_2	paul
μ_3	R_3	ringo

$\bowtie$

	$?X$	$?E$
μ_4	R_1	J@ed.ex
μ_5	R_3	R@ed.ex

Example (AND)

G : $(R_1, \text{name}, \text{john})$ $(R_2, \text{name}, \text{paul})$ $(R_3, \text{name}, \text{ringo})$
$(R_1, \text{email}, \text{J@ed.ex})$ $(R_3, \text{email}, \text{R@ed.ex})$
$(R_3, \text{webPage}, \text{www.ringo.com})$

$$[\![((?X, \text{name}, ?N) \text{ AND } (?X, \text{email}, ?E))]\!]_G$$

$$[\![(?X, \text{name}, ?N)]\!]_G \bowtie [\![(?X, \text{email}, ?E)]\!]_G$$

	$?X$	$?N$
μ_1	R_1	john
μ_2	R_2	paul
μ_3	R_3	ringo

$\bowtie$

	$?X$	$?E$
μ_4	R_1	J@ed.ex
μ_5	R_3	R@ed.ex

	$?X$	$?N$	$?E$
$\mu_1 \cup \mu_4$	R_1	john	J@ed.ex
$\mu_3 \cup \mu_5$	R_3	ringo	R@ed.ex

Example (OPT)

$$G: \begin{array}{lll} (R_1, \text{name}, \text{john}) & (R_2, \text{name}, \text{paul}) & (R_3, \text{name}, \text{ringo}) \\ (R_1, \text{email}, \text{J@ed.ex}) & & (R_3, \text{email}, \text{R@ed.ex}) \\ & & (R_3, \text{webPage}, \text{www.ringo.com}) \end{array}$$

$$[\![((?X, \text{name}, ?N) \text{ OPT } (?X, \text{email}, ?E))]\!]_G$$

Example (OPT)

$$G: \begin{array}{lll} (R_1,\ \text{name},\ \text{john}) & (R_2,\ \text{name},\ \text{paul}) & (R_3,\ \text{name},\ \text{ringo}) \\ (R_1,\ \text{email},\ \text{J@ed.ex}) & & (R_3,\ \text{email},\ \text{R@ed.ex}) \\ & & (R_3,\ \text{webPage},\ \text{www.ringo.com}) \end{array}$$

$$[\![((?X,\ \text{name},\ ?N)\ \text{OPT}\ (?X,\ \text{email},\ ?E))]\!]_G$$

$$[\![(?X,\ \text{name},\ ?N)]\!]_G \mathbin{⟕} [\![(?X,\ \text{email},\ ?E)]\!]_G$$

Example (OPT)

G :

$(R_1, \text{name}, \text{john})$ $(R_2, \text{name}, \text{paul})$ $(R_3, \text{name}, \text{ringo})$

$(R_1, \text{email}, \text{J@ed.ex})$ $(R_3, \text{email}, \text{R@ed.ex})$

$(R_3, \text{webPage}, \text{www.ringo.com})$

$$[\![((?X, \text{name}, ?N) \text{ OPT } (?X, \text{email}, ?E))]\!]_G$$

$$[\![(?X, \text{name}, ?N)]\!]_G ⟕ [\![(?X, \text{email}, ?E)]\!]_G$$

	$?X$	$?N$
μ_1	R_1	john
μ_2	R_2	paul
μ_3	R_3	ringo

Example (OPT)

G : $(R_1, \text{name}, \text{john})$ $(R_2, \text{name}, \text{paul})$ $(R_3, \text{name}, \text{ringo})$
$(R_1, \text{email}, \text{J@ed.ex})$ $(R_3, \text{email}, \text{R@ed.ex})$
$(R_3, \text{webPage}, \text{www.ringo.com})$

$$[\![((?X, \text{name}, ?N) \text{ OPT } (?X, \text{email}, ?E))]\!]_G$$

$$[\![(?X, \text{name}, ?N)]\!]_G \mathbin{⟕} [\![(?X, \text{email}, ?E)]\!]_G$$

	$?X$	$?N$
μ_1	R_1	john
μ_2	R_2	paul
μ_3	R_3	ringo

	$?X$	$?E$
μ_4	R_1	J@ed.ex
μ_5	R_3	R@ed.ex

Example (OPT)

$$G: \begin{array}{lll} (R_1,\ \text{name},\ \text{john}) & (R_2,\ \text{name},\ \text{paul}) & (R_3,\ \text{name},\ \text{ringo}) \\ (R_1,\ \text{email},\ \text{J@ed.ex}) & & (R_3,\ \text{email},\ \text{R@ed.ex}) \\ & & (R_3,\ \text{webPage},\ \text{www.ringo.com}) \end{array}$$

$$[\![((?X,\ \text{name},\ ?N)\ \text{OPT}\ (?X,\ \text{email},\ ?E))]\!]_G$$

$$[\![(?X,\ \text{name},\ ?N)]\!]_G ⟕ [\![(?X,\ \text{email},\ ?E)]\!]_G$$

	$?X$	$?N$
μ_1	R_1	john
μ_2	R_2	paul
μ_3	R_3	ringo

⟕

	$?X$	$?E$
μ_4	R_1	J@ed.ex
μ_5	R_3	R@ed.ex

Example (OPT)

$$G: \begin{array}{lll} (R_1,\ \text{name},\ \text{john}) & (R_2,\ \text{name},\ \text{paul}) & (R_3,\ \text{name},\ \text{ringo}) \\ (R_1,\ \text{email},\ \text{J@ed.ex}) & & (R_3,\ \text{email},\ \text{R@ed.ex}) \\ & & (R_3,\ \text{webPage},\ \text{www.ringo.com}) \end{array}$$

$$[\![((?X,\ \text{name},\ ?N)\ \text{OPT}\ (?X,\ \text{email},\ ?E))]\!]_G$$

$$[\![(?X,\ \text{name},\ ?N)]\!]_G \ ⟕\ [\![(?X,\ \text{email},\ ?E)]\!]_G$$

	$?X$	$?N$
μ_1	R_1	john
μ_2	R_2	paul
μ_3	R_3	ringo

⟕

	$?X$	$?E$
μ_4	R_1	J@ed.ex
μ_5	R_3	R@ed.ex

	$?X$	$?N$	$?E$
$\mu_1 \cup \mu_4$	R_1	john	J@ed.ex
$\mu_3 \cup \mu_5$	R_3	ringo	R@ed.ex
μ_2	R_2	paul	

Example (OPT)

$$G: \begin{array}{lll} (R_1, \text{name}, \text{john}) & (R_2, \text{name}, \text{paul}) & (R_3, \text{name}, \text{ringo}) \\ (R_1, \text{email}, \text{J@ed.ex}) & & (R_3, \text{email}, \text{R@ed.ex}) \\ & & (R_3, \text{webPage}, \text{www.ringo.com}) \end{array}$$

$$[\![((?X, \text{name}, ?N) \text{ OPT } (?X, \text{email}, ?E))]\!]_G$$

$$[\![(?X, \text{name}, ?N)]\!]_G \;⟕\; [\![(?X, \text{email}, ?E)]\!]_G$$

	?X	?N
μ_1	R_1	john
μ_2	R_2	paul
μ_3	R_3	ringo

⟕

	?X	?E
μ_4	R_1	J@ed.ex
μ_5	R_3	R@ed.ex

	?X	?N	?E
$\mu_1 \cup \mu_4$	R_1	john	J@ed.ex
$\mu_3 \cup \mu_5$	R_3	ringo	R@ed.ex
μ_2	R_2	paul	

Example (UNION)

$$G: \begin{array}{lll} (R_1, \text{name}, \text{john}) & (R_2, \text{name}, \text{paul}) & (R_3, \text{name}, \text{ringo}) \\ (R_1, \text{email}, \text{J@ed.ex}) & & (R_3, \text{email}, \text{R@ed.ex}) \\ & & (R_3, \text{webPage}, \text{www.ringo.com}) \end{array}$$

$$[\![((?X, \text{email}, ?\mathit{Info})\ \text{UNION}\ (?X, \text{webPage}, ?\mathit{Info}))]\!]_G$$

Example (UNION)

$$G: \begin{array}{lll} (R_1,\ \text{name},\ \text{john}) & (R_2,\ \text{name},\ \text{paul}) & (R_3,\ \text{name},\ \text{ringo}) \\ (R_1,\ \text{email},\ \text{J@ed.ex}) & & (R_3,\ \text{email},\ \text{R@ed.ex}) \\ & & (R_3,\ \text{webPage},\ \text{www.ringo.com}) \end{array}$$

$$[\![((?X,\ \text{email},\ ?Info)\ \text{UNION}\ (?X,\ \text{webPage},\ ?Info))]\!]_G$$

$$[\![(?X,\ \text{email},\ ?Info)]\!]_G \cup [\![(?X,\ \text{webPage},\ ?Info)]\!]_G$$

Example (UNION)

G : $(R_1, \text{name}, \text{john})$ $(R_2, \text{name}, \text{paul})$ $(R_3, \text{name}, \text{ringo})$
$(R_1, \text{email}, \text{J@ed.ex})$ $(R_3, \text{email}, \text{R@ed.ex})$
$(R_3, \text{webPage}, \text{www.ringo.com})$

$$[\![((?X, \text{email}, ?Info) \text{ UNION } (?X, \text{webPage}, ?Info))]\!]_G$$

$$[\![(?X, \text{email}, ?Info)]\!]_G \cup [\![(?X, \text{webPage}, ?Info)]\!]_G$$

	$?X$	$?Info$
μ_1	R_1	J@ed.ex
μ_2	R_3	R@ed.ex

Example (UNION)

$$G: \quad \begin{array}{lll} (R_1, \text{name}, \text{john}) & (R_2, \text{name}, \text{paul}) & (R_3, \text{name}, \text{ringo}) \\ (R_1, \text{email}, \text{J@ed.ex}) & & (R_3, \text{email}, \text{R@ed.ex}) \\ & & (R_3, \text{webPage}, \text{www.ringo.com}) \end{array}$$

$$[\![((?X, \text{email}, ?Info) \text{ UNION } (?X, \text{webPage}, ?Info))]\!]_G$$

$$[\![(?X, \text{email}, ?Info)]\!]_G \cup [\![(?X, \text{webPage}, ?Info)]\!]_G$$

	?X	?Info
μ_1	R_1	J@ed.ex
μ_2	R_3	R@ed.ex

	?X	?Info
μ_3	R_3	www.ringo.com

Example (UNION)

$$G: \begin{array}{lll} (R_1, \text{name}, \text{john}) & (R_2, \text{name}, \text{paul}) & (R_3, \text{name}, \text{ringo}) \\ (R_1, \text{email}, \text{J@ed.ex}) & & (R_3, \text{email}, \text{R@ed.ex}) \\ & & (R_3, \text{webPage}, \text{www.ringo.com}) \end{array}$$

$$[\![((?X, \text{email}, ?Info) \text{ UNION } (?X, \text{webPage}, ?Info))]\!]_G$$

$$[\![(?X, \text{email}, ?Info)]\!]_G \cup [\![(?X, \text{webPage}, ?Info)]\!]_G$$

	?X	?Info
μ_1	R_1	J@ed.ex
μ_2	R_3	R@ed.ex

$\cup$

	?X	?Info
μ_3	R_3	www.ringo.com

Example (UNION)

$$G: \quad \begin{array}{lll} (R_1, \text{name}, \text{john}) & (R_2, \text{name}, \text{paul}) & (R_3, \text{name}, \text{ringo}) \\ (R_1, \text{email}, \text{J@ed.ex}) & & (R_3, \text{email}, \text{R@ed.ex}) \\ & & (R_3, \text{webPage}, \text{www.ringo.com}) \end{array}$$

$$[\![((?X, \text{email}, ?\mathit{Info}) \text{ UNION } (?X, \text{webPage}, ?\mathit{Info}))]\!]_G$$

$$[\![(?X, \text{email}, ?\mathit{Info})]\!]_G \cup [\![(?X, \text{webPage}, ?\mathit{Info})]\!]_G$$

	$?X$	$?Info$
μ_1	R_1	J@ed.ex
μ_2	R_3	R@ed.ex

$\cup$

	$?X$	$?Info$
μ_3	R_3	www.ringo.com

	$?X$	$?Info$
μ_1	R_1	J@ed.ex
μ_2	R_3	R@ed.ex
μ_3	R_3	www.ringo.com

Example (SELECT)

$$G: \quad \begin{array}{lll} (R_1,\ \text{name},\ \text{john}) & (R_2,\ \text{name},\ \text{paul}) & (R_3,\ \text{name},\ \text{ringo}) \\ (R_1,\ \text{email},\ \text{J@ed.ex}) & & (R_3,\ \text{email},\ \text{R@ed.ex}) \\ & & (R_3,\ \text{webPage},\ \text{www.ringo.com}) \end{array}$$

$$[\![(\text{SELECT } \{?N, ?E\}\ ((?X,\ \text{name},\ ?N)\ \text{AND}\ (?X,\ \text{email},\ ?E)))]\!]_G$$

Example (SELECT)

$$G: \quad \begin{array}{lll} (R_1,\ \text{name},\ \text{john}) & (R_2,\ \text{name},\ \text{paul}) & (R_3,\ \text{name},\ \text{ringo}) \\ (R_1,\ \text{email},\ \text{J@ed.ex}) & & (R_3,\ \text{email},\ \text{R@ed.ex}) \\ & & (R_3,\ \text{webPage},\ \text{www.ringo.com}) \end{array}$$

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SELECT$\{?N, ?E\}$

	$?X$	$?N$	$?E$
μ_1	R_1	john	J@ed.ex
μ_2	R_3	ringo	R@ed.ex

Example (SELECT)

$$G: \quad \begin{array}{lll} (R_1, \text{name}, \text{john}) & (R_2, \text{name}, \text{paul}) & (R_3, \text{name}, \text{ringo}) \\ (R_1, \text{email}, \text{J@ed.ex}) & & (R_3, \text{email}, \text{R@ed.ex}) \\ & & (R_3, \text{webPage}, \text{www.ringo.com}) \end{array}$$

$$[\![(\text{SELECT } \{?N, ?E\} \ ((?X, \text{name}, ?N) \text{ AND } (?X, \text{email}, ?E)))]\!]_G$$

SELECT$\{?N, ?E\}$

	$?X$	$?N$	$?E$
μ_1	R_1	john	J@ed.ex
μ_2	R_3	ringo	R@ed.ex

	$?N$	$?E$
$\mu_1\|_{\{?N,?E\}}$	john	J@ed.ex
$\mu_2\|_{\{?N,?E\}}$	ringo	R@ed.ex

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 ($\wedge$, $\vee$, $\neg$)

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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- usual rules for Boolean connectives

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- R is bound$(?X)$ and $?X \in \text{dom}(\mu)$
- usual rules for Boolean connectives

Definition

FILTER : selects mappings that satisfy a condition

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

Example (FILTER)

$$G: \begin{array}{lll} (R_1, \text{name}, \text{john}) & (R_2, \text{name}, \text{paul}) & (R_3, \text{name}, \text{ringo}) \\ (R_1, \text{email}, \text{J@ed.ex}) & & (R_3, \text{email}, \text{R@ed.ex}) \\ & & (R_3, \text{webPage}, \text{www.ringo.com}) \end{array}$$

$$[\![((?X, \text{name}, ?N) \text{ FILTER } (?N = \text{ringo} \vee ?N = \text{paul}))]\!]_G$$

Example (FILTER)

G :

$(R_1, \text{name}, \text{john})$	$(R_2, \text{name}, \text{paul})$	$(R_3, \text{name}, \text{ringo})$
$(R_1, \text{email}, \text{J@ed.ex})$		$(R_3, \text{email}, \text{R@ed.ex})$
		$(R_3, \text{webPage}, \text{www.ringo.com})$

$$[\![((?X, \text{name}, ?N) \text{ FILTER } (?N = \text{ringo} \vee ?N = \text{paul}))]\!]_G$$

	$?X$	$?N$
μ_1	R_1	john
μ_2	R_2	paul
μ_3	R_3	ringo

Example (FILTER)

$$G: \begin{array}{lll} (R_1, \text{name}, \text{john}) & (R_2, \text{name}, \text{paul}) & (R_3, \text{name}, \text{ringo}) \\ (R_1, \text{email}, \text{J@ed.ex}) & & (R_3, \text{email}, \text{R@ed.ex}) \\ & & (R_3, \text{webPage}, \text{www.ringo.com}) \end{array}$$

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	$?X$	$?N$
μ_1	R_1	john
μ_2	R_2	paul
μ_3	R_3	ringo

$$?N = \text{ringo} \vee ?N = \text{paul}$$

Example (FILTER)

G :

(R_1, name, john)	(R_2, name, paul)	(R_3, name, ringo)
(R_1, email, J@ed.ex)		(R_3, email, R@ed.ex)
		(R_3, webPage, www.ringo.com)

$$[\![((?X, \text{name}, ?N) \text{ FILTER } (?N = \text{ringo} \vee ?N = \text{paul}))]\!]_G$$

	$?X$	$?N$
μ_1	R_1	john
μ_2	R_2	paul
μ_3	R_3	ringo

$?N = \text{ringo} \vee ?N = \text{paul}$

	$?X$	$?N$
μ_2	R_2	paul
μ_3	R_3	ringo

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$$G: \quad \begin{array}{lll} (R_1, \text{name}, \text{john}) & (R_2, \text{name}, \text{paul}) & (R_3, \text{name}, \text{ringo}) \\ (R_1, \text{email}, \text{J@ed.ex}) & & (R_3, \text{email}, \text{R@ed.ex}) \\ & & (R_3, \text{webPage}, \text{www.ringo.com}) \end{array}$$

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$$[\![(((?X, \text{name}, ?N) \text{ OPT } (?X, \text{email}, ?E)) \text{ FILTER } \neg \text{bound}(?E))]\!]_G$$

	$?X$	$?N$	$?E$
$\mu_1 \cup \mu_4$	R_1	john	J@ed.ex
$\mu_3 \cup \mu_5$	R_3	ringo	R@ed.ex
μ_2	R_2	paul	

Example (FILTER)

G : $(R_1,\ \text{name},\ \text{john})$ $(R_2,\ \text{name},\ \text{paul})$ $(R_3,\ \text{name},\ \text{ringo})$
$(R_1,\ \text{email},\ \text{J@ed.ex})$ $(R_3,\ \text{email},\ \text{R@ed.ex})$
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$$[\![(((?X,\ \text{name},\ ?N)\ \text{OPT}\ (?X,\ \text{email},\ ?E))\ \text{FILTER}\ \neg\,\text{bound}(?E))]\!]_G$$

	$?X$	$?N$	$?E$
$\mu_1 \cup \mu_4$	R_1	john	J@ed.ex
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$\neg\,\text{bound}(?E)$

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$\mu_1 \cup \mu_4$	R_1	john	J@ed.ex
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$\neg\, \text{bound}(?E)$

	$?X$	$?N$
μ_2	R_2	paul

SPARQL 1.1
(and some research issues)

SPARQL 1.1

A new version of SPARQL was recently released (March 2013): SPARQL 1.1

Some new features in SPARQL 1.1:

- Entailment regimes for RDFS and OWL
- Navigational capabilities: Property paths
- An operator (SERVICE) to distribute the execution of a query

Also in this version: Nesting of SELECT expressions, aggregates and some forms of negation (NOT EXISTS, MINUS)

To remember: Syntax of RDFS

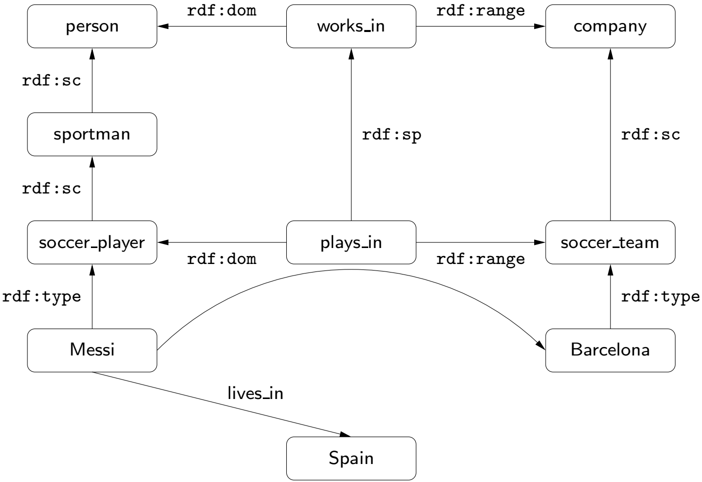
RDFS extends RDF with a schema vocabulary: subPropertyOf (`rdf:sp`), subClassOf (`rdf:sc`), domain (`rdf:dom`), range (`rdf:range`), type (`rdf:type`).

To remember: 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`).

How do we evaluate a query over RDFS data?

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 as for first-order logic.

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

An inference system for RDFS

Sub-property : $\dfrac{(\mathcal{A},\ \texttt{rdf:sp},\ \mathcal{B})\ (\mathcal{B},\ \texttt{rdf:sp},\ \mathcal{C})}{(\mathcal{A},\ \texttt{rdf:sp},\ \mathcal{C})}$

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

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

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

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

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

Entailment in RDFS

Theorem (H03,MPG09,GHM11)

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 ($G \models t$) iff t can be deduced from G by applying the inference rules a finite number of times.

An entailment regime for RDFS in SPARQL 1.1

Basic graph patterns are evaluated by considering RDFS entailment.

Definition

The evaluation of a bgp P over an RDF graph G, denoted by $[\![P]\!]_G$, is the set of mappings μ:

- $\text{dom}(\mu) = \text{var}(P)$
- For every $t \in P$: $G \models \mu(t)$

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- $\text{dom}(\mu) = \text{var}(P)$
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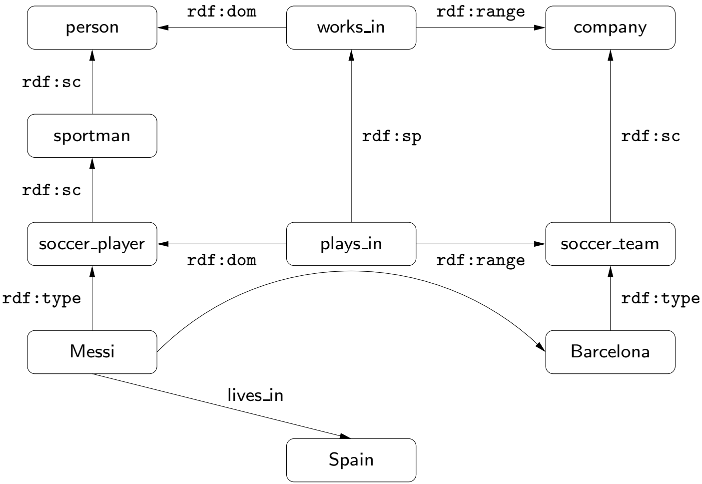
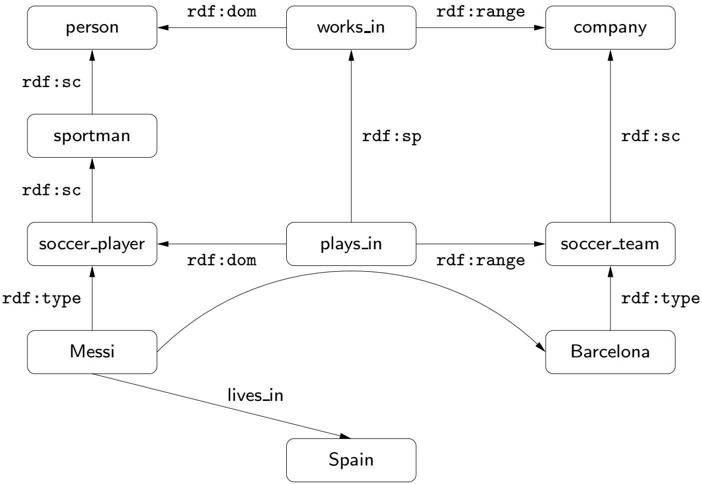
The semantics of AND, UNION, OPT, FILTER and SELECT are defined as before.

- RDFS entailment is only used at the level of bgps

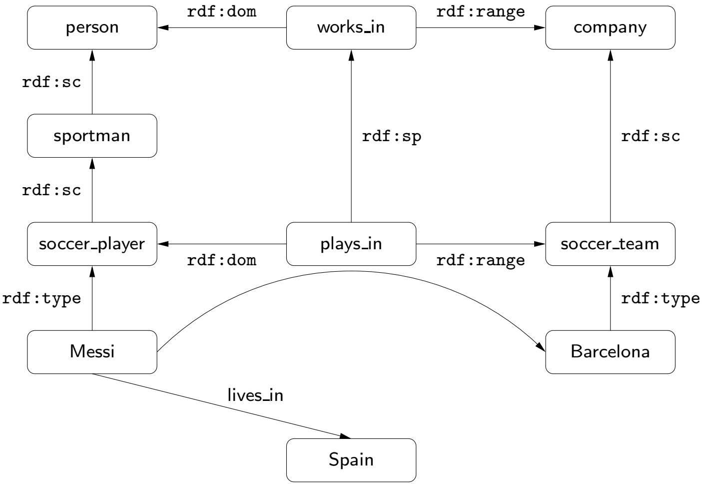
Example 1: What is the answer to (?X, `rdf:type`, person)?



Example 2: What is the answer to (Messi, rdf:type, person)?



Example 3: What is the answer to $\{(\text{Messi}, \texttt{rdf:type}, ?Y), (?Y, \texttt{rdf:sc}, \text{person})\}$?



SPARQL 1.1 can be used to query not only data but also schema information

- For example: $(?X, \texttt{rdf:sc}, \text{person})$

Entailment regimes in SPARQL 1.1: Some observations (cont'd)

Web Ontology Language (OWL): A more general ontology language for the Semantic Web

- Users can define their own axioms

  For example: every Chilean has a RUT number

Entailment regimes in SPARQL 1.1: Some observations (cont'd)

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Basic graph patterns can also be evaluated by considering OWL entailment.

- $G \models \mu(t)$ has to be defined according to the semantics of OWL

Entailment regimes in SPARQL 1.1: Some observations (cont'd)

- What are the consequences of considering entailment only at the level bgps?

Example

Let G be a graph consisting of $(\text{john}, \texttt{rdf:type}, \text{student})$ together with:

$$\left.\begin{array}{l} (\text{student}, \texttt{rdf:sc}, u) \\ (u, \text{owl:union}, l) \\ (l, \text{rdf:first}, \text{undergrad}) \\ (l, \text{rdf:rest}, r) \\ (r, \text{rdf:first}, \text{grad}) \\ (r, \text{rdf:rest}, \text{rdf:nil}) \end{array}\right\} \text{axiom } \text{student} \sqsubseteq (\text{undergrad} \sqcup \text{grad})$$

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What should be the answer to
$P = ((?X, \texttt{rdf:type}, \text{undergrad}) \text{ UNION } (?X, \texttt{rdf:type}, \text{grad}))$?

- Under the current semantics: $[\![P]\!]_G = \emptyset$

Entailment regimes in SPARQL 1.1: Some observations (cont'd)

It is possible to define a certain-answers semantics for SPARQL 1.1.

- Previous example shows that this semantics does not coincide with the official semantics of SPARQL 1.1

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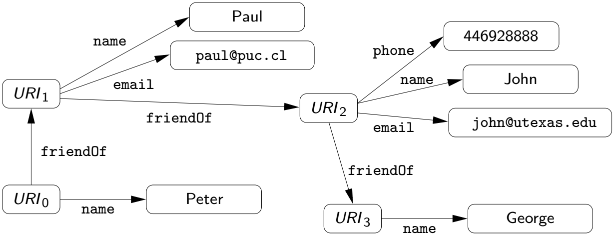
Open issues

- How natural is the semantics of SPARQL 1.1? Is it a good semantics? Why?
- Under which (natural) restrictions these two semantics coincide?

SPARQL provides limited navigational capabilities



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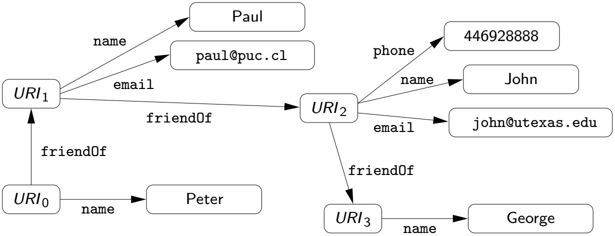
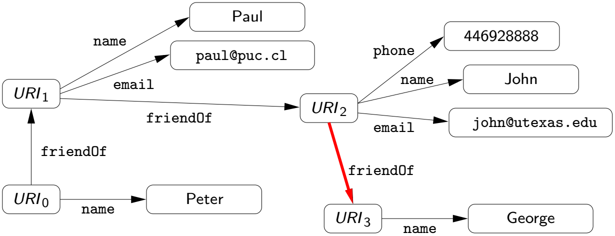


(SELECT ?X ((?X, friendOf, ?Y) AND (?Y, name, George)))

SPARQL provides limited navigational capabilities



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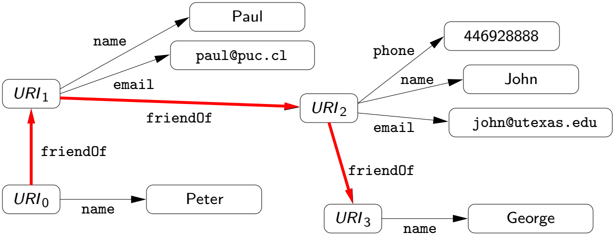

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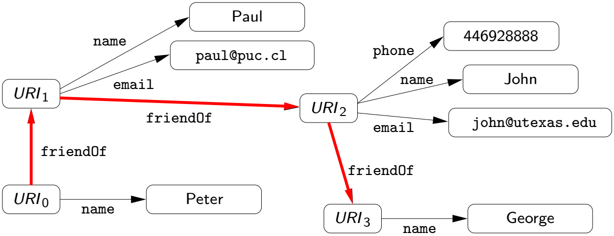
A possible solution: Property paths



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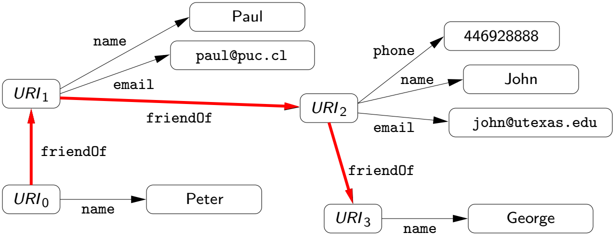

(SELECT ?X ((?X, (friendOf)*, ?Y) AND (?Y, name, George)))

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 $a \in U$

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where $a \in U$

Other expressions are allowed:

$\hat{}exp$	:	inverse path
$!(a_1 \mid \ldots \mid a_n)$	:	a URI which is not one of a_i $(1 \leq i \leq n)$

Evaluating property paths

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

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$$
\begin{array}{rcl}
[\![a]\!]_G & = & \{(x,y) \mid (x,a,y) \in G\} \\
[\![exp_1/exp_2]\!]_G & = & \{(x,y) \mid \exists z\ (x,z) \in [\![exp_1]\!]_G \text{ and} \\
 & & \qquad\qquad\qquad (z,y) \in [\![exp_2]\!]_G\}
\end{array}
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[\![exp_1|exp_2]\!]_G & = & [\![exp_1]\!]_G \cup [\![exp_2]\!]_G \\
[\![exp^*]\!]_G & = & \{(a,a) \mid a \text{ is a URI in } G\} \cup [\![exp]\!]_G \cup \\
 & & [\![exp/exp]\!]_G \cup [\![exp/exp/exp]\!]_G \cup \cdots
\end{array}
$$

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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- $(?X, (\text{friendOf})^*, ?Y)$: Verifies whether there exists a path of friends of arbitrary length from $?X$ to $?Y$
- $(?X, (\texttt{rdf:sc})^*, \text{person})$: Verifies whether the value stored in $?X$ is a subclass of person
- $(?X, (\texttt{rdf:sp})^*, ?Y)$: Verifies whether the value stored in $?X$ is a subproperty of the value stored in $?Y$

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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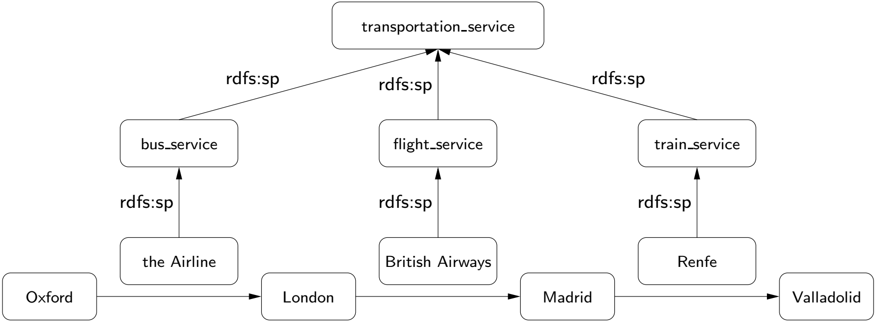
Other cases are defined analogously.

Example

- $((?X, \text{KLM}/(\text{KLM})^*, ?Y)$ FILTER $\neg(?X = ?Y))$: It is possible to go from $?X$ to $?Y$ by using the airline KLM, where $?X$, $?Y$ are different cities

SPARQL 1.1: Entailment regimes and property paths

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



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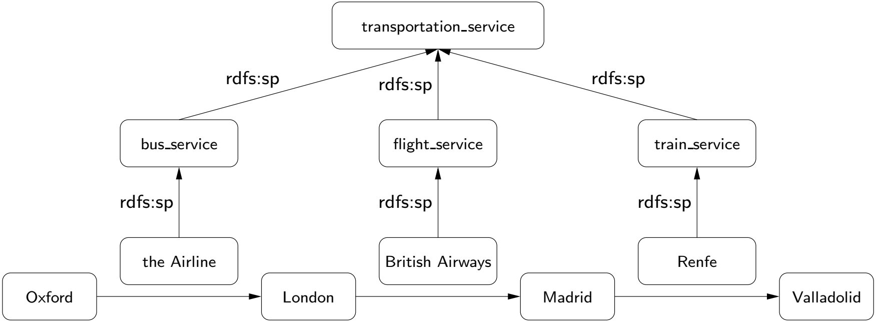

In SPARQL 1.1: $(?X, \text{transportation\_service}^*, ?Y)$

Navigational capabilities in SPARQL 1.1: Some observations

Previous query can be expressed in SPARQL 1.1 as the intermediate form of navigation involves RDFS vocabulary.

Navigational capabilities in SPARQL 1.1: Some observations

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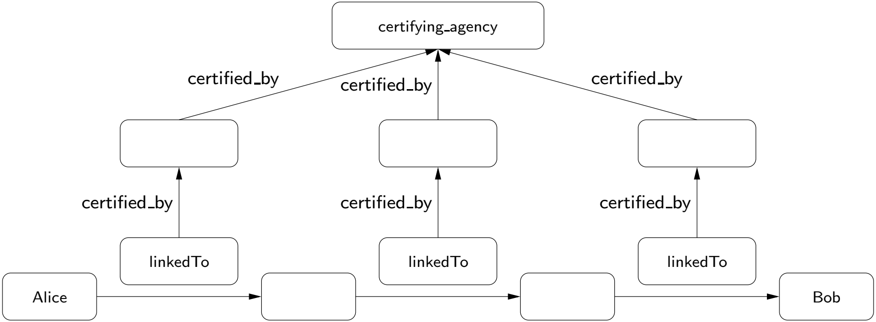
Not expressible: List pairs *a*, *b* of persons that are connected through a path of nodes certified by certifying_agency [RK13]:



Navigational capabilities in SPARQL 1.1: Some observations (cont'd)

- Some proposals solve the aforementioned issues: nSPARQL [PAG10], nested monadically defined queries [RK13], triple algebra [LRV13]
  - RDFS entailment can be handled in these proposals by using navigational capabilities

Navigational capabilities in SPARQL 1.1: Some observations (cont'd)

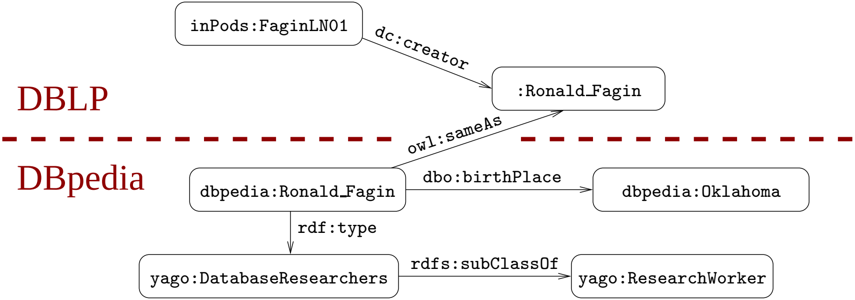
- Some proposals solve the aforementioned issues: nSPARQL [PAG10], nested monadically defined queries [RK13], triple algebra [LRV13]
  - RDFS entailment can be handled in these proposals by using navigational capabilities

Open issues

- How can OWL entailment be handled in these proposals?
- What navigational capabilities should be added to SPARQL 1.1?
- There is a need for query languages that can return paths

RFD graphs can be interconnected

```
       : <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/>
```



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 .
  SERVICE <http://dbpedia.org/sparql> {
    ?Person     owl:sameAs     ?Author .
    ?Person     dbo:birthPlace dbpedia:Oklahoma . }
}
```

Federation in SPARQL 1.1

New rule to generate graph patterns:

- If P is a graph pattern and $c \in (U \cup V)$, then (SERVICE c P) is a graph pattern.

Federation in SPARQL 1.1

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- If P is a graph pattern and $c \in (U \cup V)$, then (SERVICE c P) is a graph pattern.

We will define the semantics of this new operator.

- This corresponds with the official semantics for (SERVICE c P) with $c \in U$
- (SERVICE $?X$ P) is allowed in the official specification of SPARQL 1.1, but its semantics is not defined

Semantics of SERVICE

$\mathrm{ep}(\cdot)$: Partial function from U to the set of all RDF graphs

- If $c \in \mathrm{dom}(\mathrm{ep})$, then $\mathrm{ep}(c)$ is the RDF graph associated with the endpoint accessible via c

Semantics of SERVICE

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Definition [BACP13]

The evaluation of $P = (\text{SERVICE}\ \ c\ P_1)$ over an RDF graph G is defined as:

- if $c \in \mathrm{dom}(\mathrm{ep})$, then $[\![P]\!]_G = [\![P_1]\!]_{\mathrm{ep}(c)}$
- if $c \in U \setminus \mathrm{dom}(\mathrm{ep})$, then $[\![P]\!]_G = \{\mu_\emptyset\}$ (where $\mu_\emptyset$ is the mapping with empty domain)
- if $c \in V$, then

$$[\![P]\!]_G \quad = \quad \bigcup_{a \in \mathrm{dom}(\mathrm{ep})} \Big([\![P_1]\!]_{\mathrm{ep}(a)} \bowtie \{c \to a\} \Big),$$

Are variables useful in SERVICE queries?

Consider the query:

$$(?X, \text{service\_address}, ?Y) \text{ AND } (\text{SERVICE } ?Y \ (?N, \text{email}, ?E))$$

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$$(?X, \text{service\_address}, ?Y) \text{ AND } (\text{SERVICE } ?Y \ (?N, \text{email}, ?E))$$

There is a simple strategy to compute the answer to this query.

- Can this strategy be generalized?

How can we evaluate SERVICE queries?

We need some notion of boundedness

- A variable $?X$ is bound in a graph pattern P if for every RDF graph G and every $\mu \in [\![P]\!]_G$, it holds that $?X \in \text{dom}(\mu)$ and $\mu(?X) \in U$

First attempt: Graph pattern P can be evaluated if for every sub-pattern (SERVICE $?X$ P_1) of P, it holds that $?X$ is bound in P

- $?Y$ is bound in
  $(?X, \text{service\_address}, ?Y)$ AND (SERVICE $?Y$ $(?N, \text{email}, ?E)$)

The first attempt: Too restrictive

Consider the query:

$$(?X, \text{service\_description}, ?Z) \text{ UNION}$$
$$\Big((?X, \text{service\_address}, ?Y) \text{ AND } (\text{SERVICE } ?Y \ (?N, \text{email}, ?E))\Big)$$

$?Y$ is not bound in this query, but there is a simple strategy to evaluate it.

The first attempt: Not appropriate for nested SERVICE operators

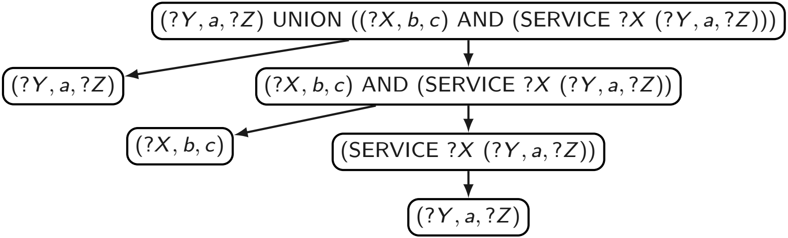
Consider the query:

$$
\begin{aligned}
&(?U_1, \text{related\_with}, ?U_2) \ \ \text{AND} \\
&\qquad\qquad \Big[\text{SERVICE } ?U_1 \ \Big((?N, \text{email}, ?E) \ \ \text{OPT} \\
&\qquad\qquad\qquad\qquad (\text{SERVICE } ?U_2 \ (?N, \text{phone}, ?F))\Big)\Big]
\end{aligned}
$$

Solving the problems . . .

Notation: $\mathcal{T}(P)$ is the *parse* tree of P, in which every node corresponds to a sub-pattern of P

Parse tree of $(?Y, a, ?Z)$ UNION $((?X, b, c)$ AND (SERVICE $?X$ $(?Y, a, ?Z)))$:



A more appropriate notion of boundedness

Definition [BACP13]

A graph pattern P is service-bound if for every node u of $\mathcal{T}(P)$ with label (SERVICE ?X P_1), it holds that:

- there exists a node v of $\mathcal{T}(P)$ with label P_2 such that v is an ancestor of u in $\mathcal{T}(P)$ and ?X is bound in P_2
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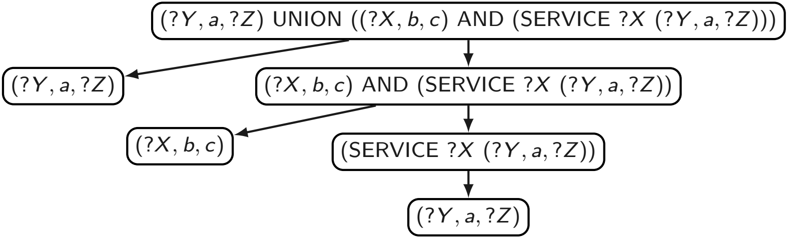

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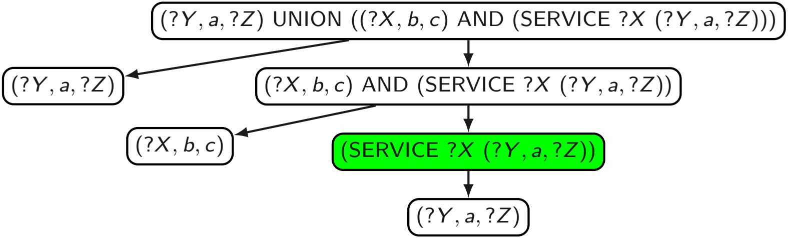

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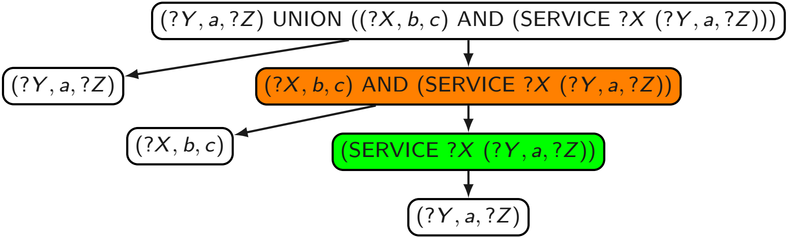

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Examples:

$\boxed{(?Y, a, ?Z)}$

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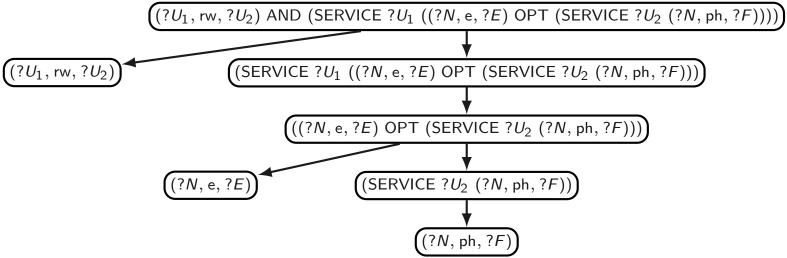

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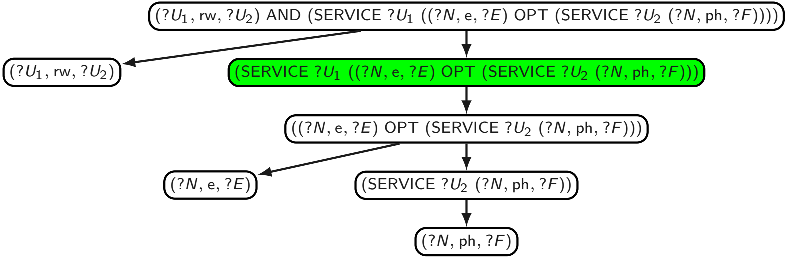

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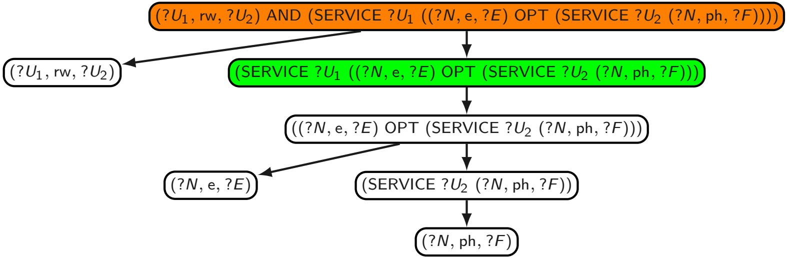

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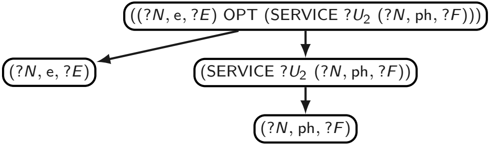

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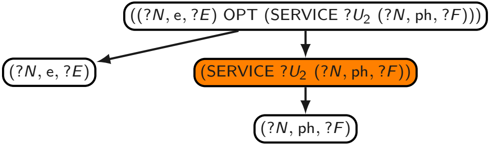

A more appropriate notion of boundedness (cont'd)

But we still have a problem:

Proposition (BACP13)

The problem of verifying, given a graph pattern P, whether P is service-bound is undecidable.

We consider a (syntactic) sufficient condition for service-boundedness.

An appropriate notion: Service-safeness

The set of strongly bound variables in P, denoted by $\mathrm{SB}(P)$, is recursively defined as follows:

- if P is a bgp, then $\mathrm{SB}(P) = \mathrm{var}(P)$
- if $P = (P_1 \text{ AND } P_2)$, then $\mathrm{SB}(P) = \mathrm{SB}(P_1) \cup \mathrm{SB}(P_2)$
- if $P = (P_1 \text{ UNION } P_2)$, then $\mathrm{SB}(P) = \mathrm{SB}(P_1) \cap \mathrm{SB}(P_2)$
- if $P = (P_1 \text{ OPT } P_2)$, then $\mathrm{SB}(P) = \mathrm{SB}(P_1)$
- if $P = (P_1 \text{ FILTER } R)$, then $\mathrm{SB}(P) = \mathrm{SB}(P_1)$
- if $P = (\text{SERVICE } c\ P_1)$, then $\mathrm{SB}(P) = \emptyset$

An appropriate notion: Service-safeness (cont'd)

Definition [BACP13]

A graph pattern P is service-safe if for every node u of $\mathcal{T}(P)$ with label (SERVICE $?X$ P_1), it holds that:

- there exists a node v of $\mathcal{T}(P)$ with label P_2 such that v is an ancestor of u in $\mathcal{T}(P)$ and $?X \in \mathrm{SB}(P_2)$
- P_1 is service-safe

If P is service-safe, then there is a strategy to evaluate P without considering all possible SPARQL endpoints.

An appropriate notion: Service-safeness (cont'd)

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- P_1 is service-safe

If P is service-safe, then there is a strategy to evaluate P without considering all possible SPARQL endpoints.

Open issue

Is service-safeness the right condition to ensure that a query containing the SERVICE operator can be executed? Why?

Take-home message

- RDF is the framework proposed by the W3C to represent information in the Web
- SPARQL is the W3C recommendation query language for RDF (January 2008)
- SPARLQ 1.1 is the new version of SPARQL (March 2013)
- SPARQL 1.1 includes some interesting and useful new features
  - Entailment regimes for RDFS and OWL, navigational capabilities and an operator to distribute the execution of a query
  - There are some interesting open issues about these features

Thank you!

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