Federation and Navigation in SPARQL 1.1

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Outline

SPARQL query language for RDF

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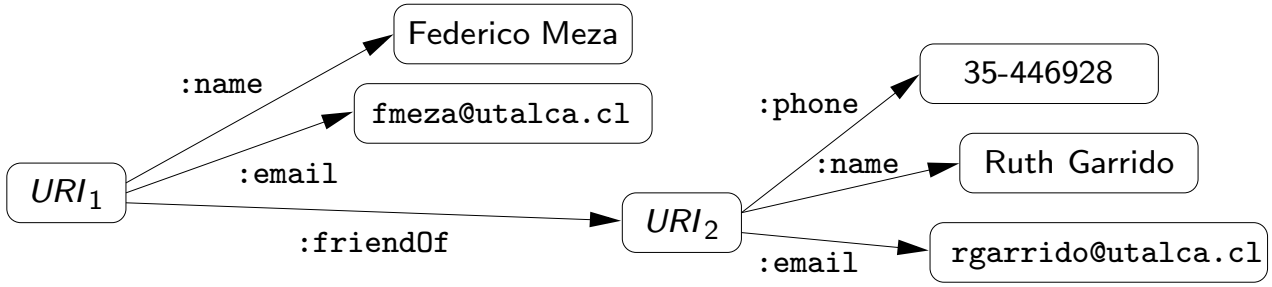
RDF Graph:



RDF-triples: (URI_2, `:email`, `rgarrido@utalca.cl`)

SPARQL query language for RDF

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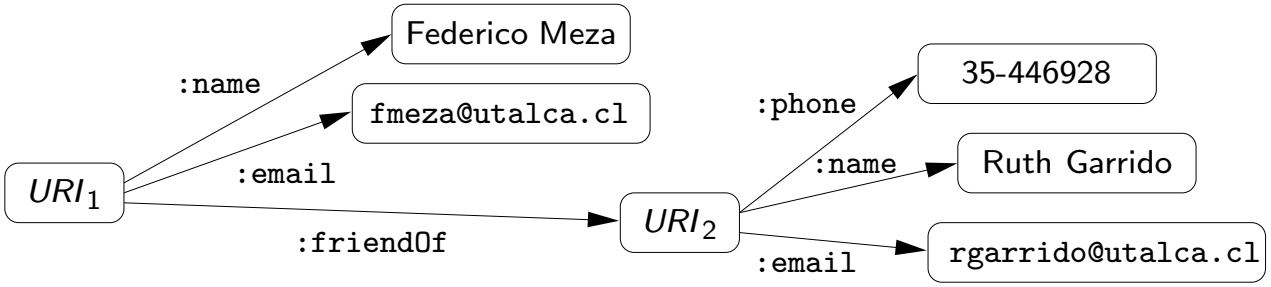

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SPARQL Query:

```
SELECT ?N
WHERE
{
  ?X :name ?N .


}
```

SPARQL query language for RDF

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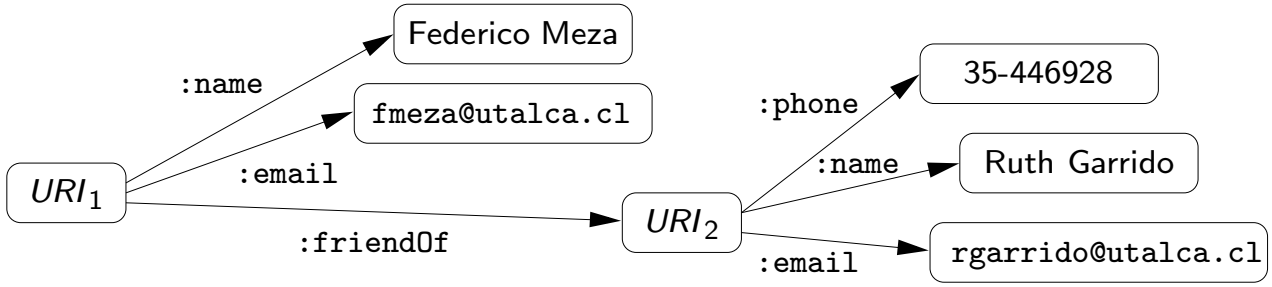

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SPARQL Query:

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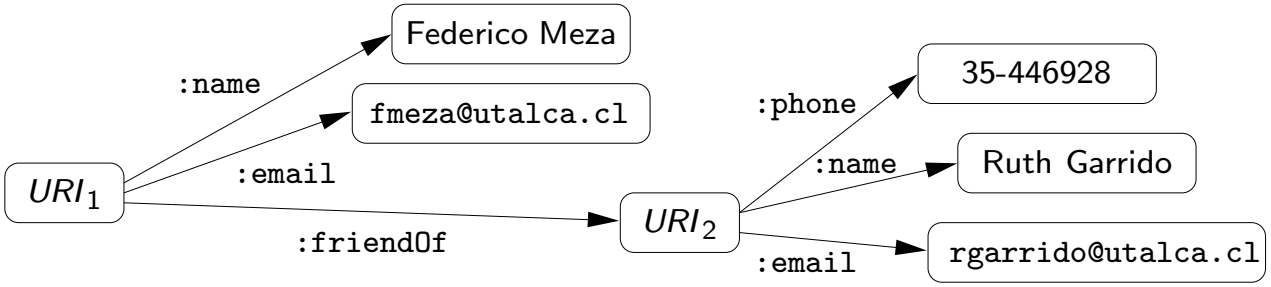


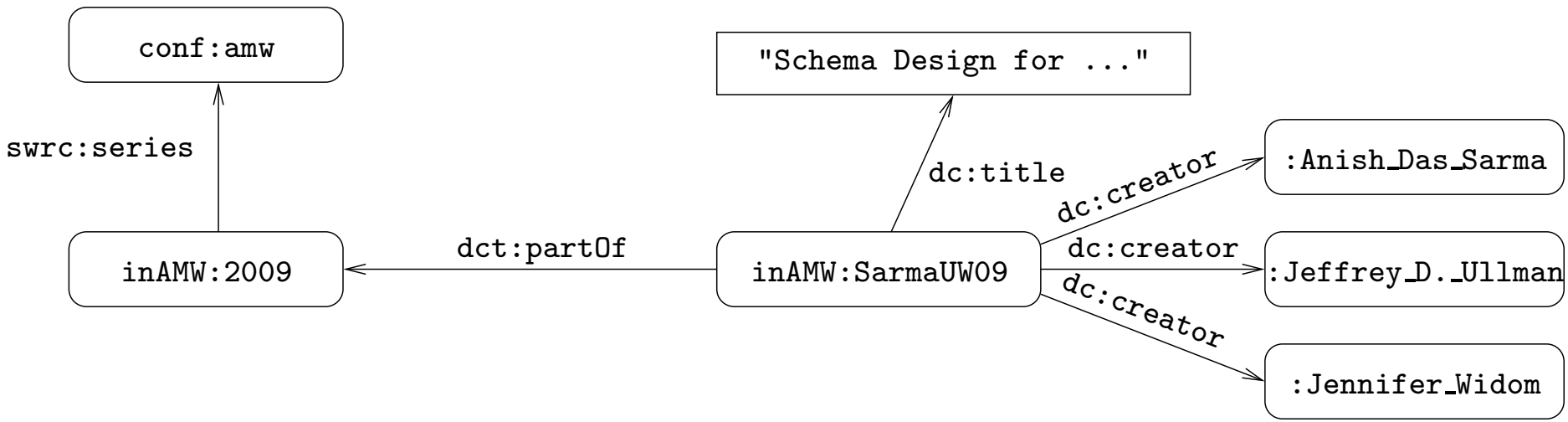
RDF-triples: (URI_2, `:email`, `rgarrido@utalca.cl`)

SPARQL Query:

```
SELECT ?N ?E
WHERE
{
  ?X :name ?N .
  ?X :email ?E .
  ?X :friendOf ?Y . ?Y :name "Ruth Garrido"
}
```

An example of an RDF graph to query: DBLP

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



SPARQL: A Simple RDF Query Language

Example: Authors that have published in ISWC

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```
SELECT ?Author
```

SPARQL: A Simple RDF Query Language

Example: Authors that have published in ISWC

```
SELECT ?Author
WHERE
{



}
```

SPARQL: A Simple RDF Query Language

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

Example: Authors that have published in ISWC

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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

SPARQL: A Simple RDF Query Language

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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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- Grouping

```
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 {{ P1 .
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    P4 }

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Interesting features of pattern matching on graphs

- Grouping
- Optional parts

```
SELECT ?X1 ?X2 ...
 {{ P1 .
    P2
    OPTIONAL { P5 }  }

  { P3 .
    P4
    OPTIONAL { P7 }  }

 }
```

But things can become more complex...

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      OPTIONAL { P8 }  }  }
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- Union of patterns

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 UNION
 { P9 }}
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But things can become more complex...

Interesting features of pattern matching on graphs

- Grouping
- Optional parts
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- Filtering
- ...
- + several new features in the upcoming version: federation, navigation

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What is the (formal) *meaning* of a general SPARQL query?

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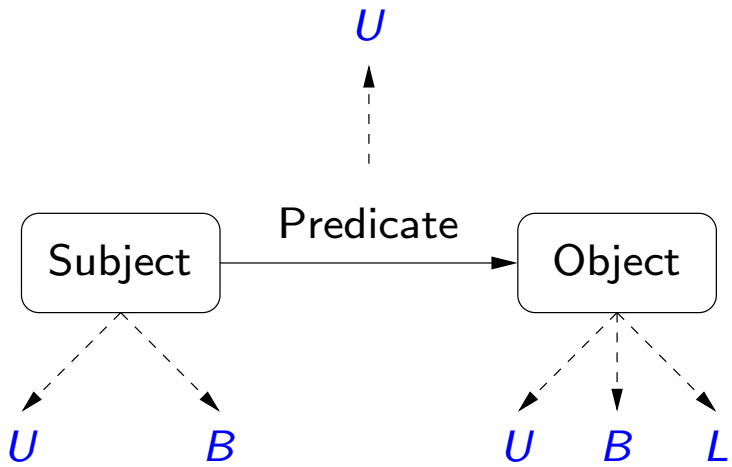
RDF triples and graphs

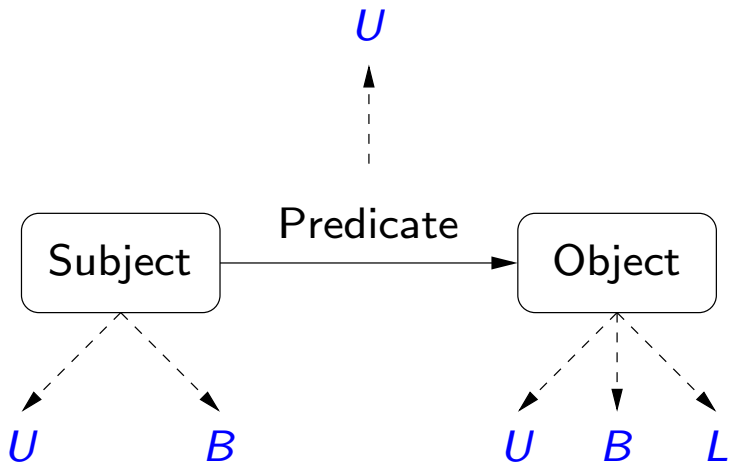


U : set of URIs

B : set of blank nodes

L : set of literals

RDF triples and graphs



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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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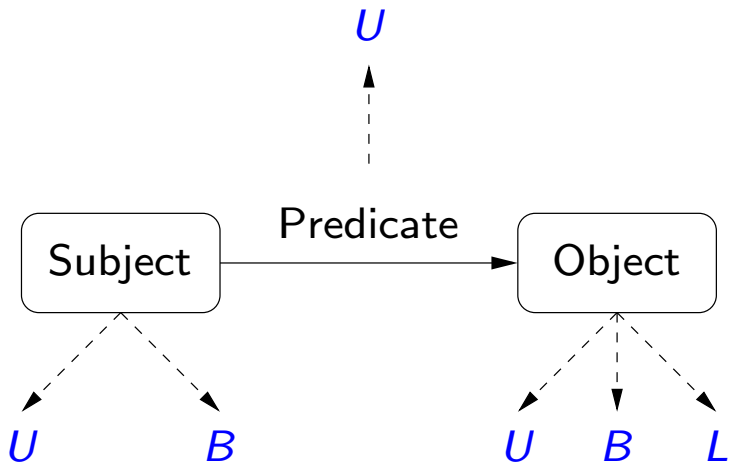

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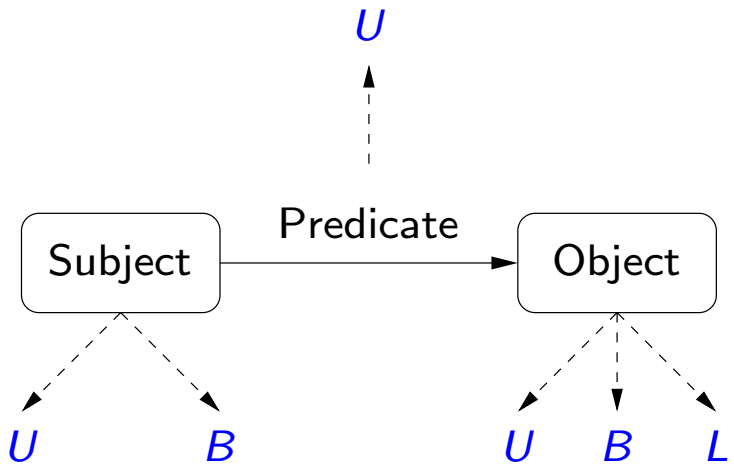

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In this talk, we do not consider blank nodes

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A standard algebraic syntax

- Triple patterns: just RDF triples + variables (from a set V)

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

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

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- Graph patterns: full parenthesized algebra

original SPARQL syntax

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`{ P1 FILTER ( R ) }`	$(P_1 \text{ FILTER } R)$

A standard algebraic syntax (cont.)

- 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

$$\mu : \quad V \rightarrow U \cup L$$

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$$t = (?X, \text{name}, ?Name)$$

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

The semantics of triple patterns

Definition

The evaluation of triple patter t over a graph G, denoted by $[\![t]\!]_G$, is the set of all mappings μ such that:

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- $\text{dom}(\mu)$ is exactly the set of variables occurring in t
- $\mu(t) \in G$

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

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

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

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$$\{\ \mu_\emptyset = \{\ \}\ \}$$

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Compatible mappings: mappings that can be merged.

Definition

The mappings μ_1, μ_2 are *compatibles* iff they agree in their *shared variables*:

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	$?X$	$?Y$	$?U$	$?V$
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μ_2	R_1		J@edu.ex	
μ_3			P@edu.ex	R_2

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Compatible mappings: mappings that can be merged.

Definition

The mappings μ_1, μ_2 are *compatibles* iff they agree in their *shared variables*:

- $\mu_1(?X) = \mu_2(?X)$ for every $?X \in \text{dom}(\mu_1) \cap \text{dom}(\mu_2)$.

$\mu_1 \cup \mu_2$ is also a mapping.

Example

	$?X$	$?Y$	$?U$	$?V$
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

$\mu_\emptyset = \{\ \}$ is compatible with every mapping.

Sets of mappings and operations

Let M_1 and M_2 be sets of mappings:

Definition

Join: $M_1 \bowtie M_2$

- $\{\mu_1 \cup \mu_2 \mid \mu_1 \in M_1, \mu_2 \in M_2,$ and μ_1, μ_2 are compatibles$\}$
- extending mappings in M_1 with compatible mappings in M_2

will be used to define AND

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Definition

Join: $M_1 \bowtie M_2$

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- extending mappings in M_1 with compatible mappings in M_2

will be used to define AND

Definition

Union: $M_1 \cup M_2$

- $\{\mu \mid \mu \in M_1$ or $\mu \in M_2\}$
- mappings in M_1 plus mappings in M_2 (the usual set union)

will be used to define UNION

Sets of mappings and operations

Definition

Difference: $M_1 \setminus M_2$

- $\{\mu \in M_1 \mid$ for all $\mu' \in M_2$, μ and μ' are not compatibles$\}$
- mappings in M_1 that cannot be extended with mappings in M_2

Sets of mappings and operations

Definition

Difference: $M_1 \setminus M_2$

- $\{\mu \in M_1 \mid$ for all $\mu' \in M_2$, μ and μ' are not compatibles$\}$
- mappings in M_1 that cannot be extended with mappings in M_2

Definition

Left outer join: $M_1 \mathbin{⟕} M_2 = (M_1 \bowtie M_2) \cup (M_1 \setminus M_2)$

- extension of mappings in M_1 with compatible mappings in M_2
- plus the mappings in M_1 that cannot be extended.

will be used to define OPT

Semantics of general graph patterns

Definition

Given a graph G the evaluation of a pattern is recursively defined

the base case is the evaluation of a triple pattern.

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Given a graph G the evaluation of a pattern is recursively defined

- $[\![(P_1 \text{ AND } P_2)]\!]_G = [\![P_1]\!]_G \bowtie [\![P_2]\!]_G$
- $[\![(P_1 \text{ UNION } P_2)]\!]_G = [\![P_1]\!]_G \cup [\![P_2]\!]_G$

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- $[\![(P_1 \text{ UNION } P_2)]\!]_G = [\![P_1]\!]_G \cup [\![P_2]\!]_G$
- $[\![(P_1 \text{ OPT } P_2)]\!]_G = [\![P_1]\!]_G \mathbin{⟕} [\![P_2]\!]_G$

the base case is the evaluation of a triple pattern.

Example (AND)

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

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

Example (AND)

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

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

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Example (AND)

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

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

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

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

Example (AND)

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

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

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

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	$?X$	$?N$
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μ_2	R_2	paul
μ_3	R_3	ringo

$\bowtie$

	$?X$	$?E$
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Example (AND)

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

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

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

	$?X$	$?N$
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 :

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

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

Example (OPT)

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

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

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

Example (OPT)

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

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

Example (OPT)

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

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

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

	$?X$	$?N$
μ_1	R_1	john
μ_2	R_2	paul
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	$?X$	$?E$
μ_4	R_1	J@ed.ex
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Example (OPT)

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

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	$?X$	$?N$
μ_1	R_1	john
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⟕

	$?X$	$?E$
μ_4	R_1	J@ed.ex
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Example (OPT)

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

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

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

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

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

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

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

Example (UNION)

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

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

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

Example (UNION)

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

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

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

	$?X$	$?\mathit{Info}$
μ_1	R_1	J@ed.ex
μ_2	R_3	R@ed.ex

Example (UNION)

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

	$?X$	$?Info$
μ_3	R_3	www.ringo.com

Example (UNION)

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

$\cup$

	$?X$	$?Info$
μ_3	R_3	www.ringo.com

Example (UNION)

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

$\cup$

	$?X$	$?Info$
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

Boolean filter expressions (value constraints)

In filter expressions we consider

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

A mapping μ satisfies

- $?X = c$ if $\mu(?X) = c$
- $?X = ?Y$ if $\mu(?X) = \mu(?Y)$
- bound$(?X)$ if μ is defined in $?X$, i.e. $?X \in \text{dom}(\mu)$

Satisfaction of value constraints

- If P is a graph pattern and R is a value constraint then (P FILTER R) is also a graph pattern.

Satisfaction of value constraints

- If P is a graph pattern and R is a value constraint then $(P \text{ FILTER } R)$ is also a graph pattern.

Definition

Given a graph G

- $[\![(P \text{ FILTER } R)]\!]_G = \{\mu \in [\![P]\!]_G \mid \mu \text{ satisfies } R\}$
  i.e. mappings in the evaluation of P that satisfy R.

Example (FILTER)

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

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

Example (FILTER)

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

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

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

Example (FILTER)

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

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

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

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

Example (FILTER)

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

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

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

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

	$?X$	$?N$
μ_2	R_2	paul
μ_3	R_3	ringo

Example (FILTER)

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

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

Example (FILTER)

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

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

	$?X$	$?N$	$?E$
$\mu_1 \cup \mu_4$	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 : $(R_1, \text{name}, \text{john})$ $(R_1, \text{email}, \text{J@ed.ex})$ $(R_2, \text{name}, \text{paul})$ $(R_3, \text{name}, \text{ringo})$ $(R_3, \text{email}, \text{R@ed.ex})$ $(R_3, \text{webPage}, \text{www.ringo.com})$

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

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

$\neg \text{bound}(?E)$

Example (FILTER)

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

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

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

$\neg \text{bound}(?E)$

	$?X$	$?N$
μ_2	R_2	paul

Example (FILTER)

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

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

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

$\neg \text{bound}(?E)$

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(a *non-monotonic* query)

Why do we need/want to formalize SPARQL

A formalization is beneficial

- clarifying corner cases
- helping in the implementation process
- providing solid foundations (we can actually prove properties!)

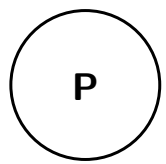
The evaluation decision problem

Evaluation problem for SPARQL patterns

Input: A mapping μ, an RDF graph G
a graph pattern P

Output: Is the mapping μ in the evaluation of pattern P
over the RDF graph G

Brief complexity-theory reminder



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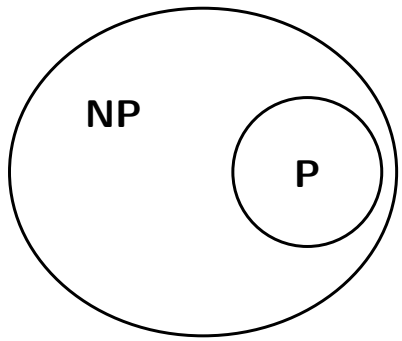

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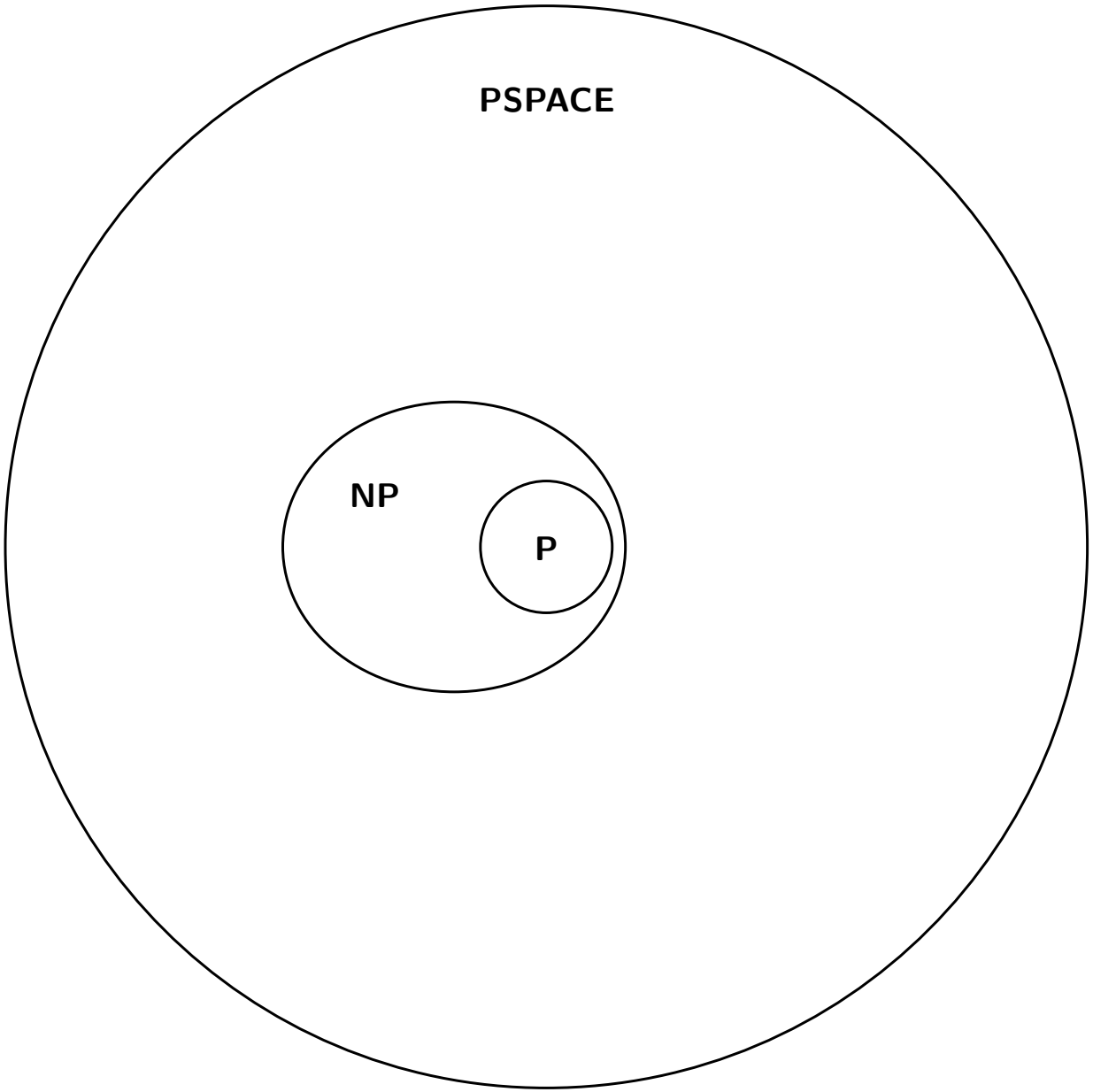

Complexity of the evaluation problem

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For patterns using only the AND *operator,*

the evaluation problem is in **P**

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Theorem (PAG09,SML10)

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Good news: evaluation in **P** if the query is fixed (*data complexity*)

Well–designed patterns

Can we find a natural fragment with better complexity?

Definition

An AND-OPT pattern is *well–designed* iff for every OPT in the pattern

$$(\ \cdots\cdots\cdots\ \ (\ \ A\ \ \text{OPT}\ \ B\ \ )\ \ \cdots\cdots\cdots\ )$$

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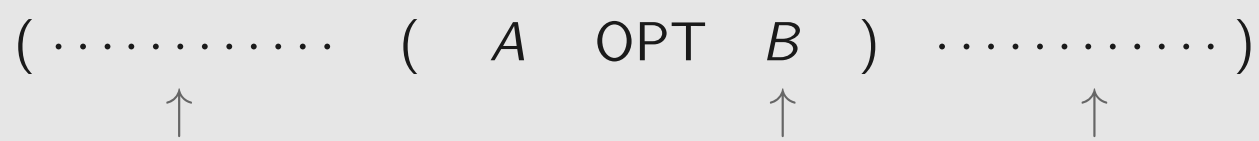

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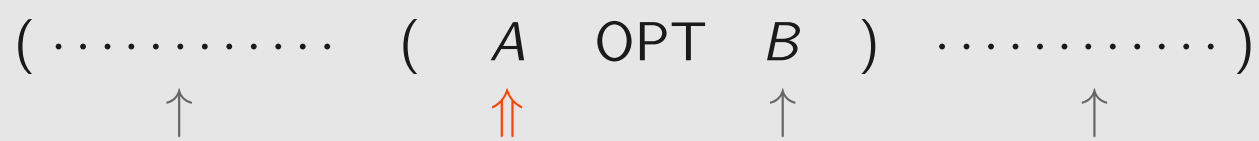

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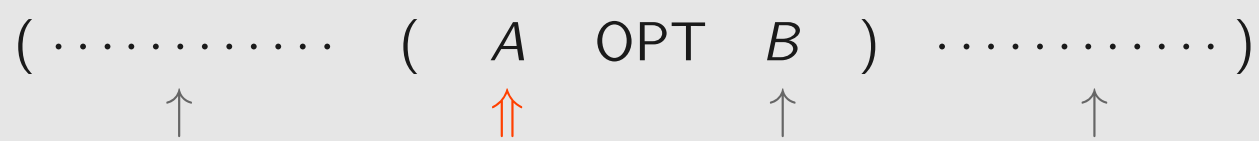

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$$\big[\,\big[\,(?Y, \text{name}, \text{paul})\ \text{OPT}\ (?X, \text{email}, ?Z)\,\big]\ \ \text{AND}\ \ (?X, \text{name}, \text{john})\,\big]$$

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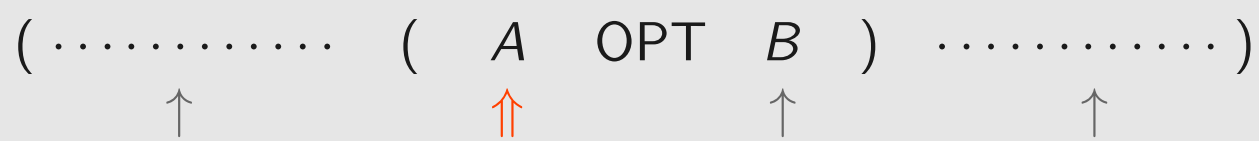

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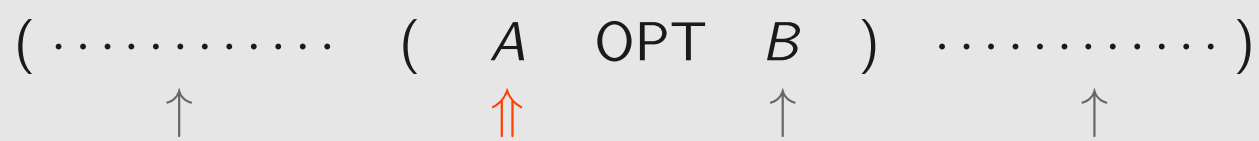

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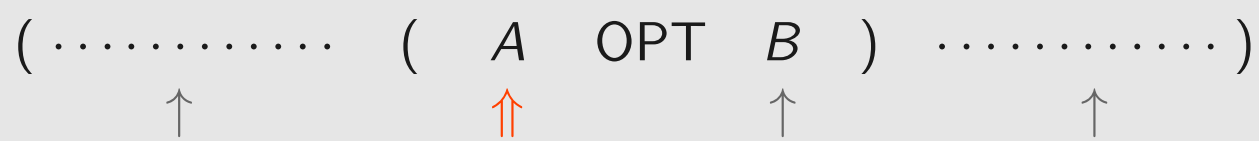

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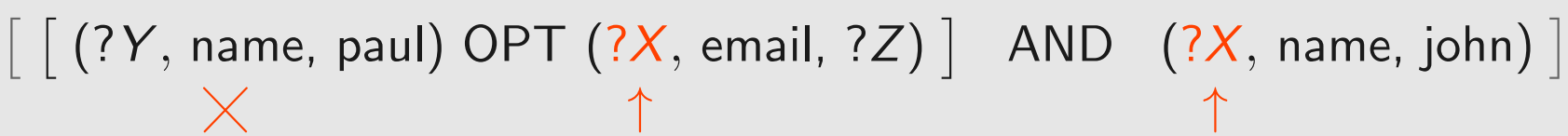

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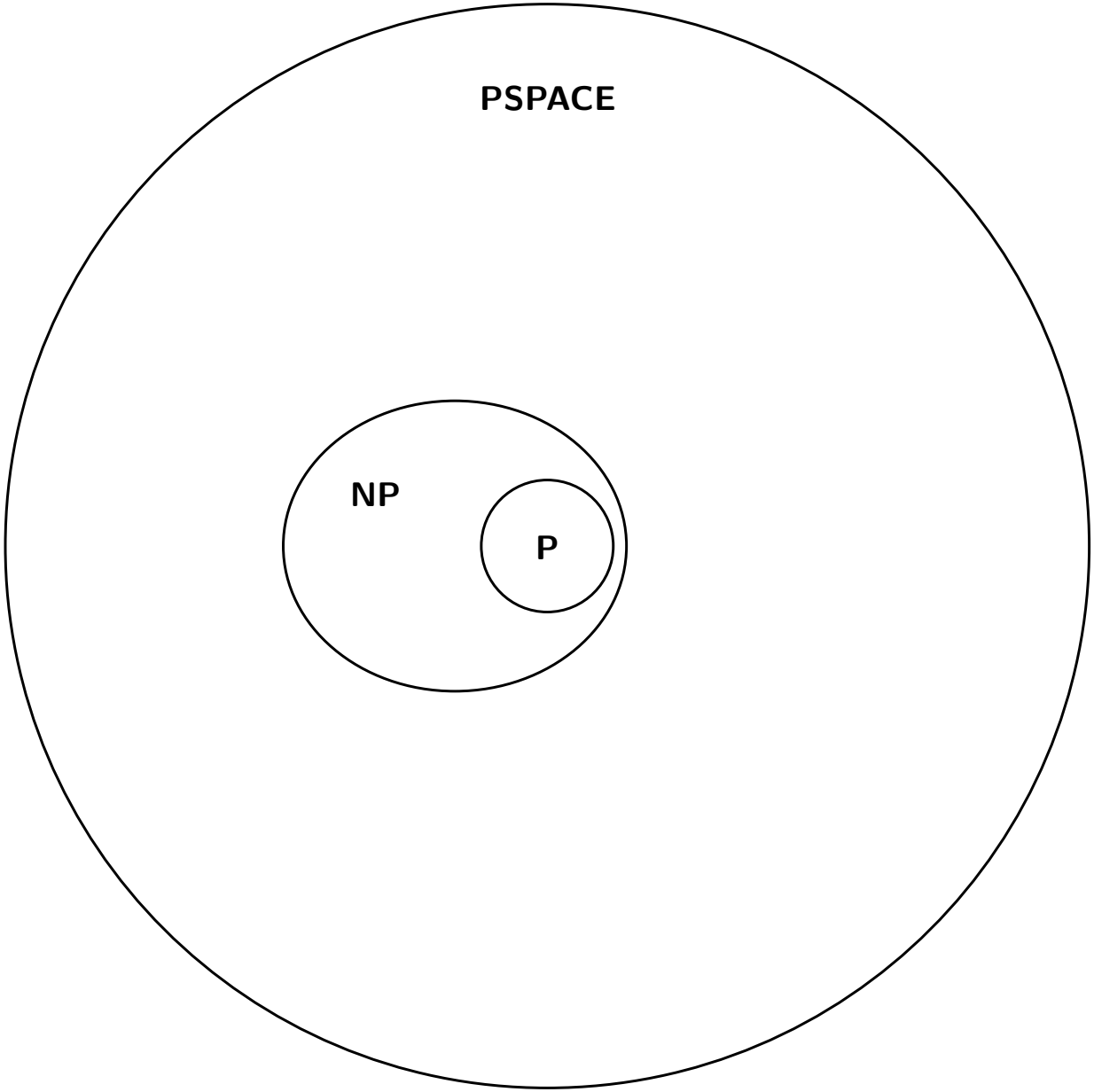

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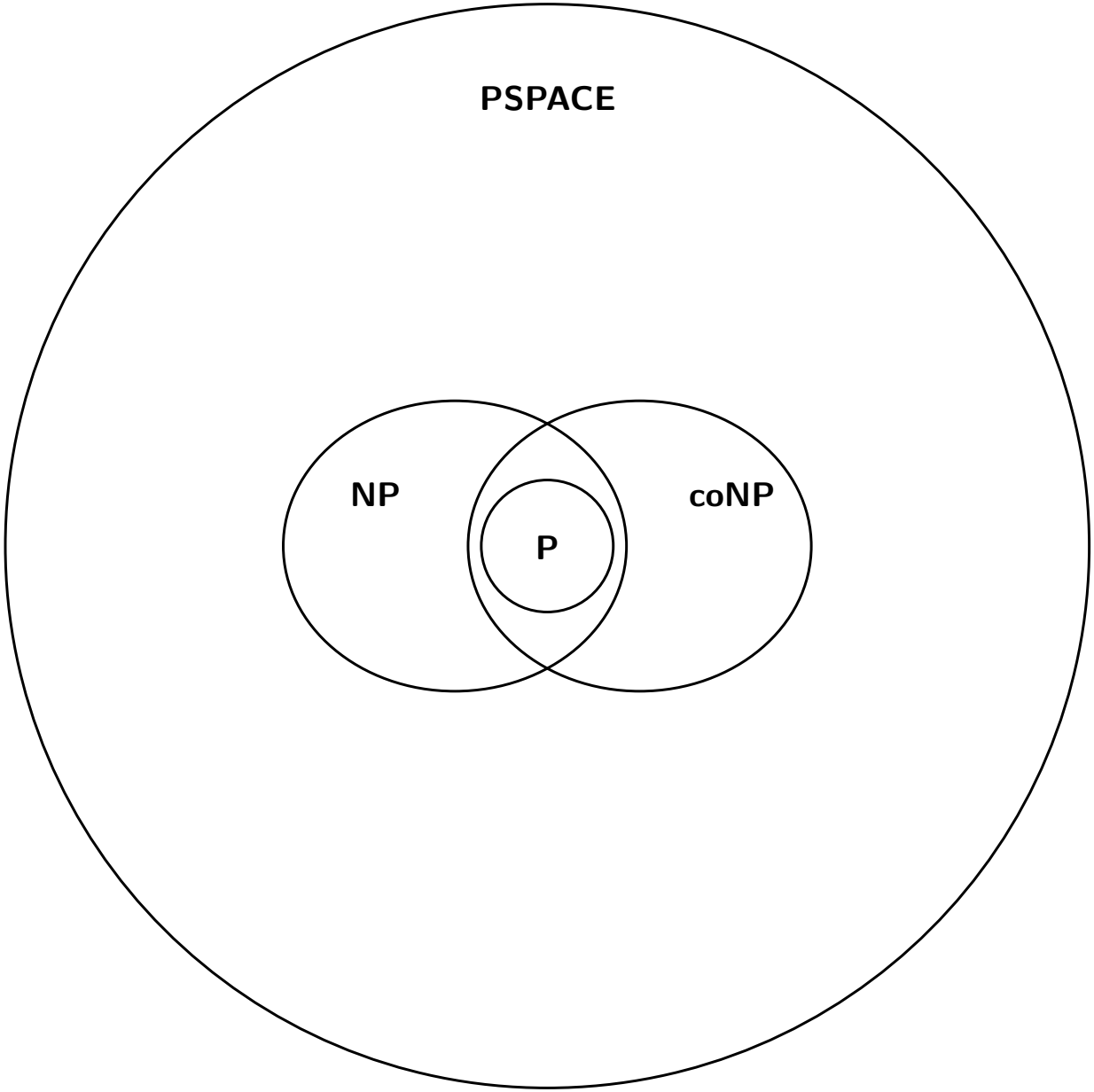

Evaluation of well-designed patterns is in coNP-complete

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Well-designed patterns also allow to study static analysis:

Theorem (LPPS12)

Equivalence of well-designed SPARQL patterns is in **NP**

SELECT (a.k.a. projection)

Besides graph patterns, SPARQL 1.0 allow *result forms*
the most simple is SELECT

Definition

A SELECT query is an expression

$$(\text{SELECT } W \; P)$$

where P is a graph pattern and W is a set of variables, or $*$

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Definition

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where P is a graph pattern and W is a set of variables, or $*$

The evaluation of a SELECT query against G is

- $[\![(\text{SELECT } W\ P)]\!]_G = \{\mu_{|W} \mid \mu \in [\![P]\!]_G\}$
  where $\mu_{|W}$ is the restriction of μ to domain W.
- $[\![(\text{SELECT } *\ P)]\!]_G = [\![P]\!]_G$

Example (SELECT)

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

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

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

Example (SELECT)

G :
(R_1, name, john)
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$\mu_1\|_{\{?N,?E\}}$	john	J@ed.ex
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SPARQL 1.1 introduces several new features

In SPARQL 1.1:

- (SELECT W P) can be used as any other graph pattern
  (ASK P) can be used as a constraint in FILTER
  $\Rightarrow$ sub-queries
- Aggregations via ORDER-BY plus COUNT, SUM, etc.
- More important for us: Federation and Navigation

Outline

SPARQL endpoints and the SERVICE operator

- *SPARQL endpoints* are services that accepts HTTP requests asking for SPARQL queries
  - `http://www.w3.org/wiki/SparqlEndpoints` lists some
- SPARQL 1.1 allows to *mix* local and remote queries to endpoints via the SERVICE operator

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



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

   SERVICE dbpedia:service
         { ?Author dbpedia:birthPlace ?Place . }
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```

Syntax of SERVICE

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If $c \in U$, $?X$ is a variable, and P is a graph pattern then

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- SERVICE graph pattern are included recursively in the algebra of graph patterns
- Variables are included in the SERVICE syntax to allow *dynamic* choosing of endpoints

Semantics of SERVICE

We assume the existence of a partial function

$$\text{ep} : U \rightarrow \text{RDF graphs}$$

intuitively, ep(c) is the (default) graph associated to the SPARQL endpoint defined by c

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but the interesting case is when the endpoint is a variable...

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can we effectively evaluate a SERVICE query?

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- only for the obtained mappings evaluate the SERVICE on endpoint $\mu(?Y)$

Unbounded SERVICE queries

What about this pattern?

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Idea: force the SERVICE variable to be *bound* in every solution.

Boundedness

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A variable $?X$ is *bound* in graph pattern P if
for every graph G and every $\mu \in [\![P]\!]_G$ it holds that:

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- Assume P does not mention $?X$, and let $Q = ((?X, ?Y, ?Z)$ UNION $P)$:

  $?X$ is bound in Q iff P is not satisfiable.

Undecidability of boundedness

Proof idea

- From [AG08]: it is undecidable to check if a SPARQL pattern P is satisfiable (if $[\![P]\!]_G \neq \emptyset$ for some G).
- Assume P does not mention $?X$, and let $Q = ((?X, ?Y, ?Z)$ UNION $P)$:

  $?X$ is bound in Q iff P is not satisfiable.

Undecidable: the SPARQL engine cannot check for boundedness...

A sufficient condition for boundedness

Definition [BAC11]

The set of *strongly bounded* variables in a pattern P, denoted by $\mathrm{SB}(P)$ is defined recursively as follows.

- if P is a triple pattern t, then $\mathrm{SB}(P) = \mathrm{var}(t)$
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($\mathrm{SB}(P)$ can be efficiently computed)

(Strongly) boundedness is not enough

Are we happy now?

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we need to define what the *important* part is...

Parse tree of a pattern

We need first to formalize the tree of subexpressions of a pattern

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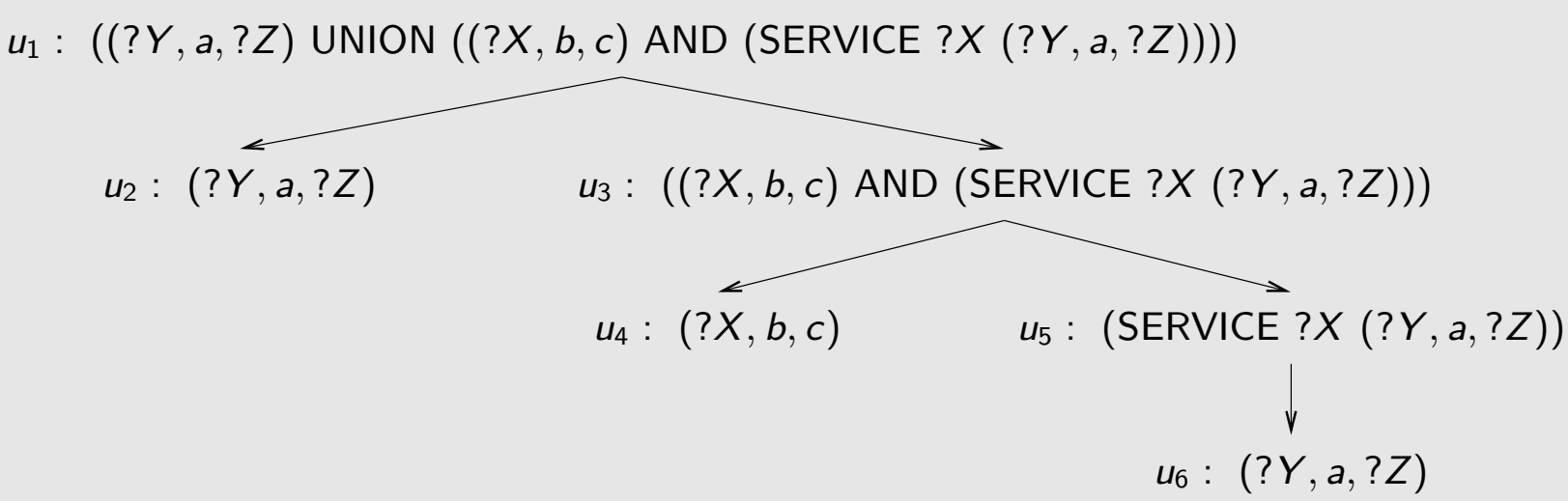

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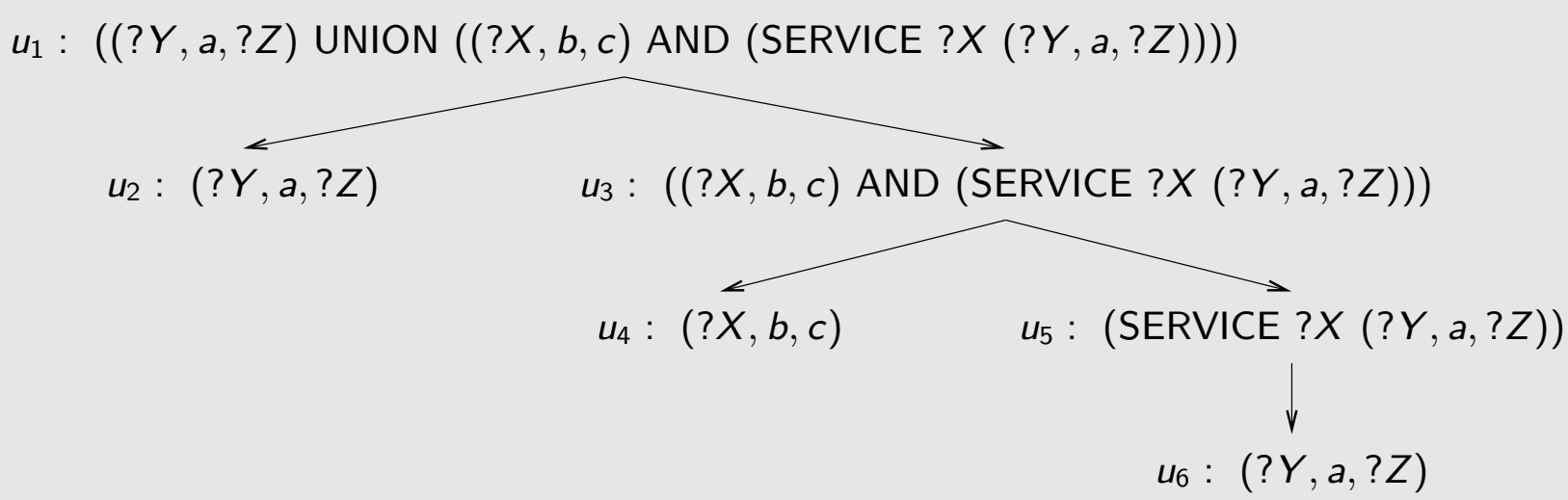

We denote by $\mathcal{T}(P)$ the tree of subexpressions of P.

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Notion of boundedness considering the important part

Definition

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Exercise: prove the theorem.

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We need a decidable sufficient condition.

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We finally have our desired decidable condition.

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is not service-safe.

Closing words on SERVICE

SERVICE: several interesting research question

- Optimization (rewriting, reordering, containment?)
- Cost analysis: in practice we cannot query all that we may want
- Different endpoints provide different *completeness* certificates (regarding the data they return)
- Several implementations challenges

Outline

SPARQL 1.0 has very limited navigational capabilities

Assume a graph with cities and connections with RDF triples like:

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but do we want to integrate Datalog and SPARQL?

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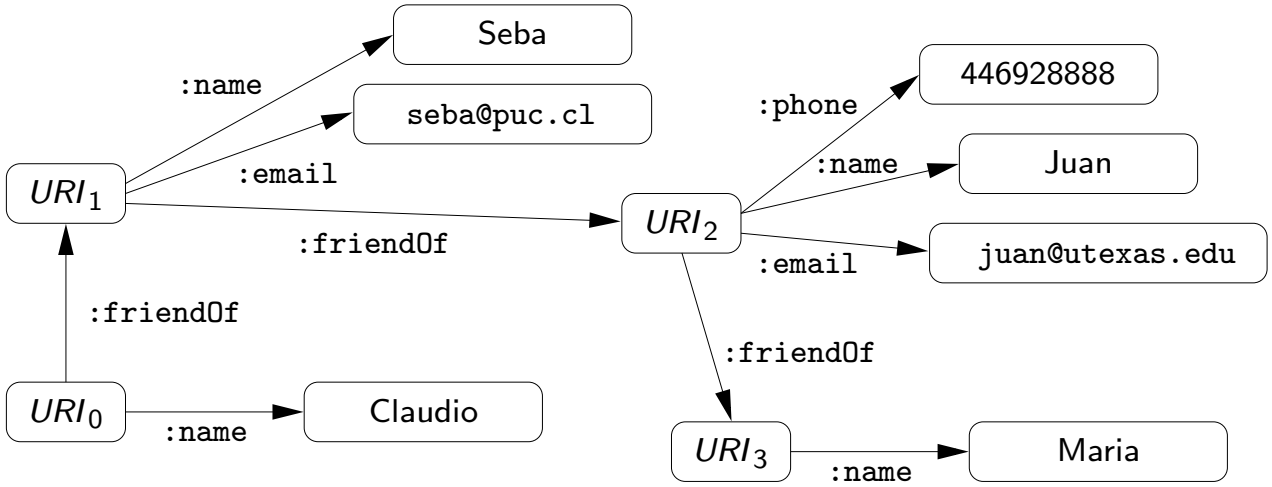

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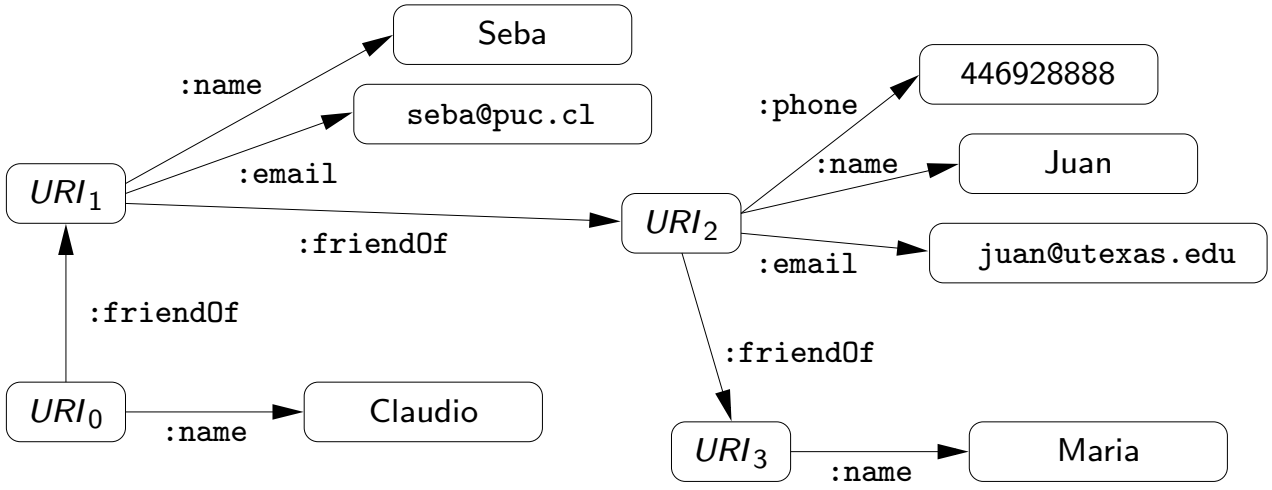


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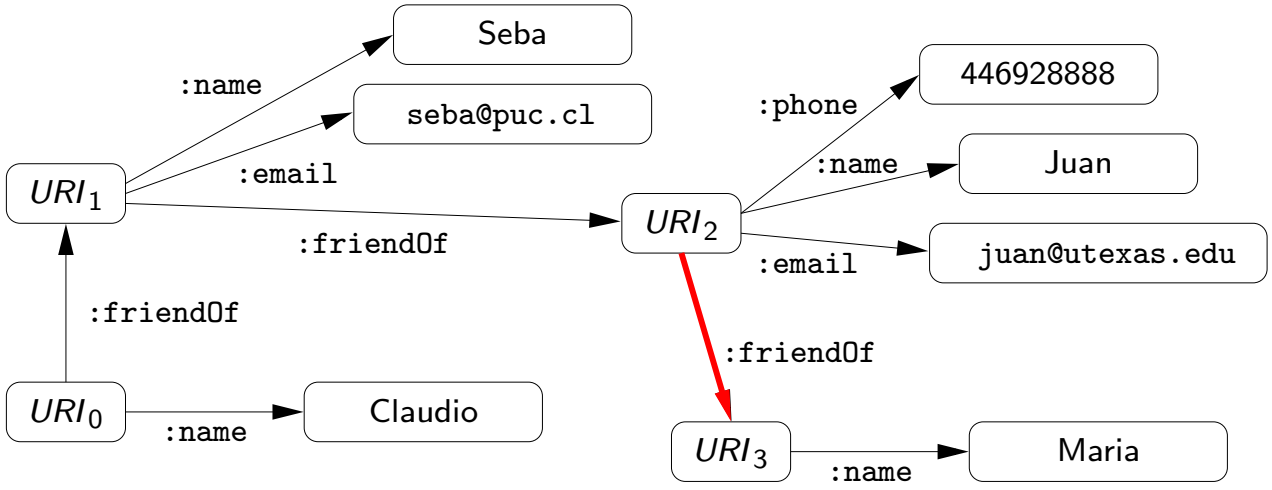


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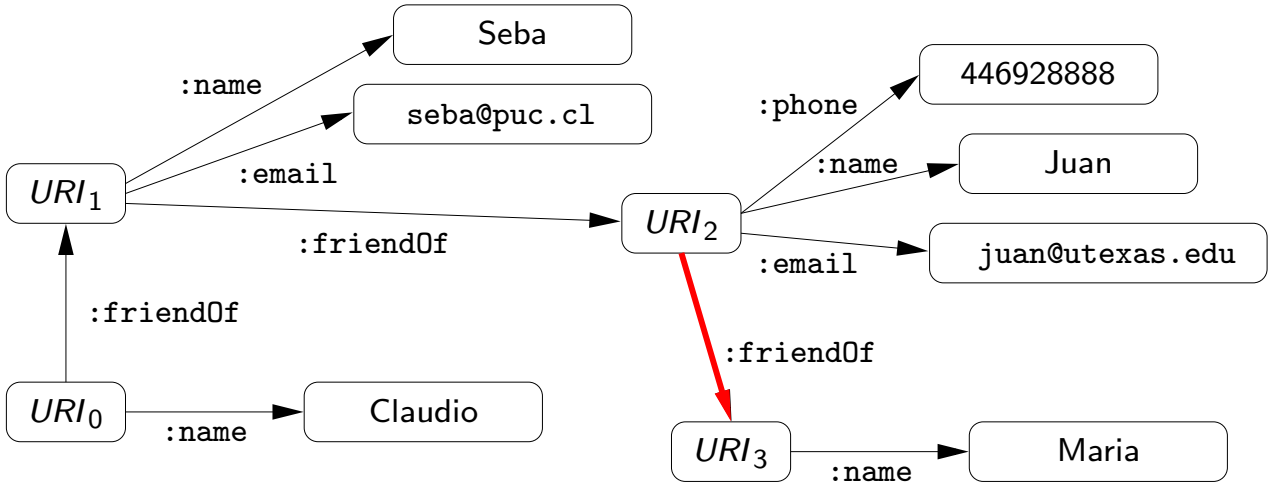


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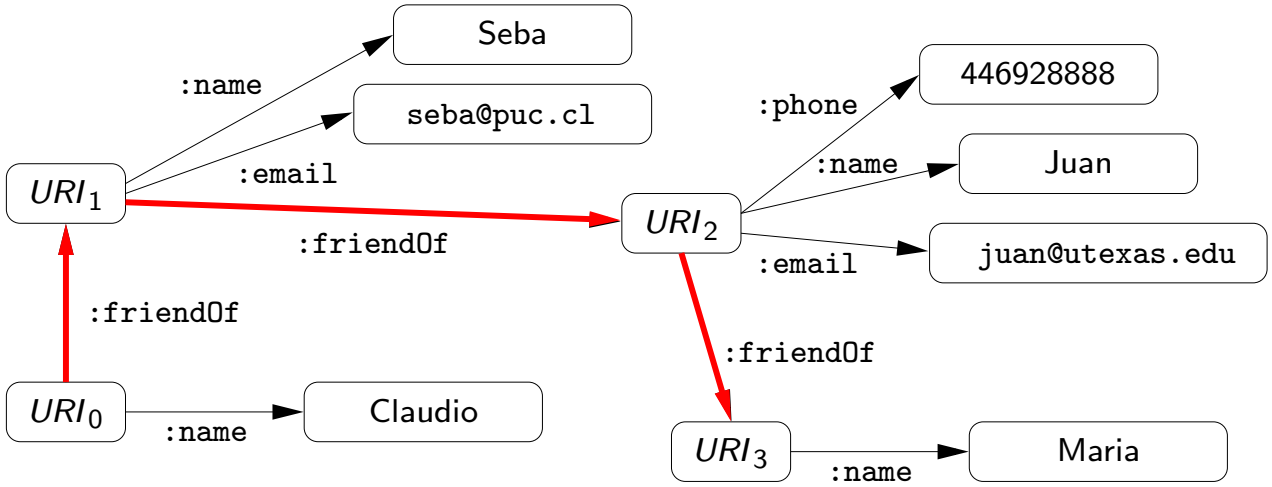


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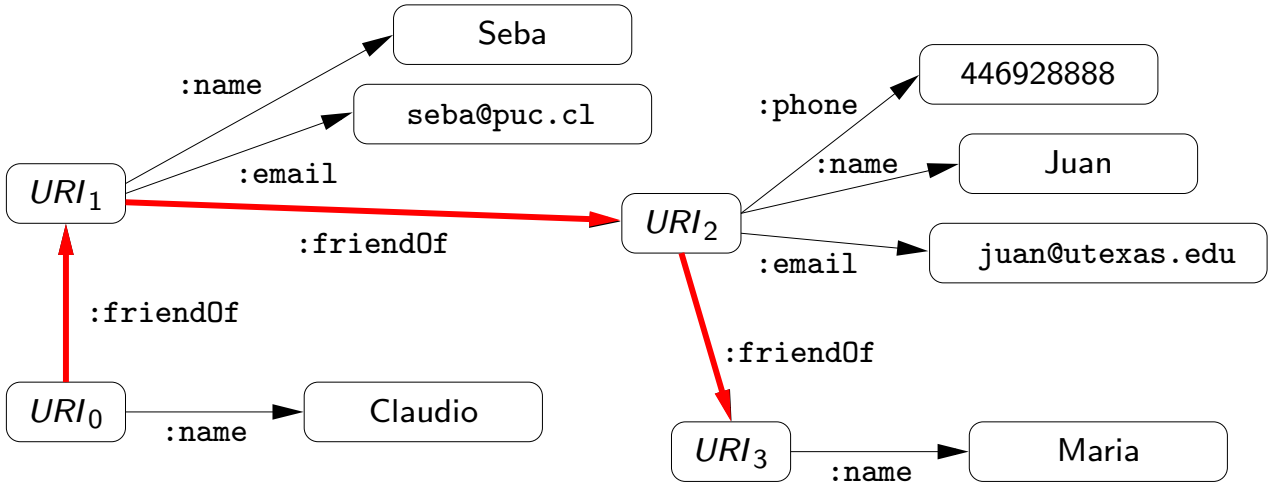


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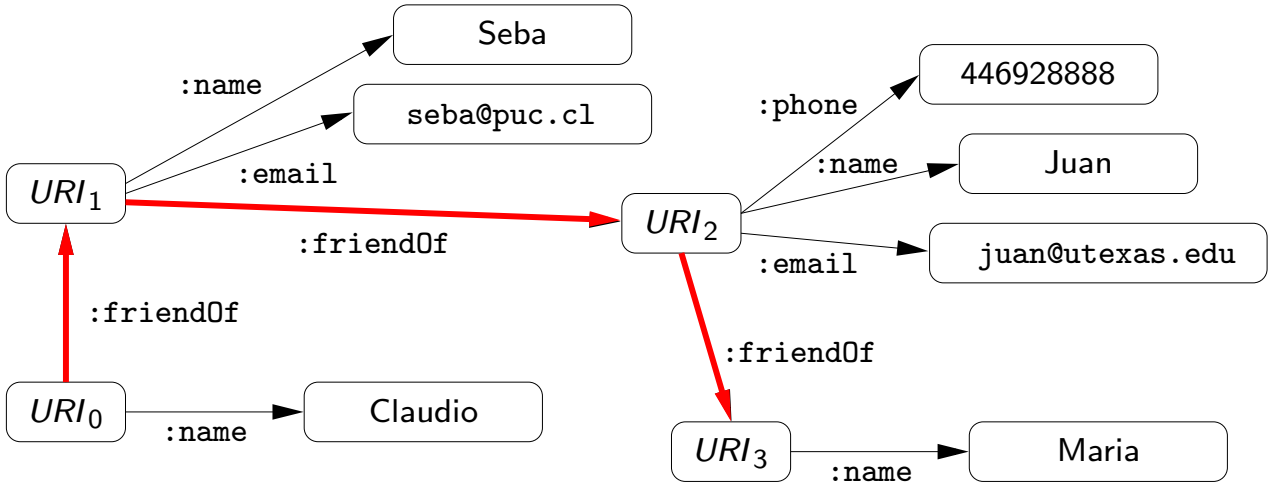


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Idea: navigate RDF graphs using *regular expressions*

General navigation using regular expressions

Regular expressions define sets of strings using

- concatenation: /
- disjunction: |
- Kleene star: *

Example

Consider strings composed of symbols `a` and `b`

`a/(b)*/a`

defines strings of the form $\texttt{abbb}\cdots\texttt{bbba}$.

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Idea: use regular expressions to define paths

- a path `p` satisfies a regular expression `r` if the string composed of the sequence of edges of `p` satisfies expression `r`

Interesting navigational queries

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```
{ ?X (:conn)* ?Y .
  ?X (:conn)* ?Z .
  ?Y :sameSchool ?Z }
```

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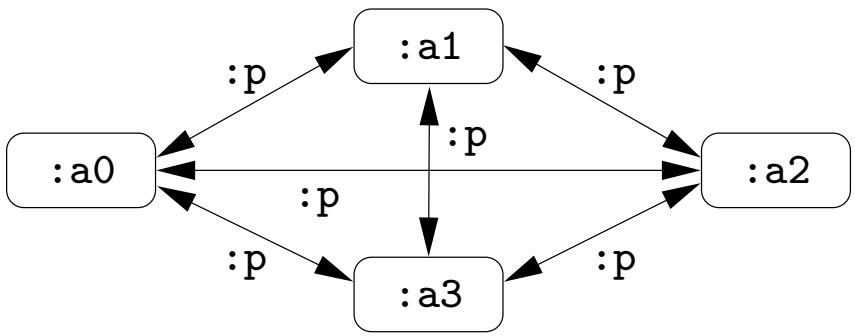
The following experimental study is based on [ACP12].

SPARQL 1.1 implementations had a poor performance

Data:

- *cliques* (complete graphs) of different size
- from 2 nodes (87 bytes) to 13 nodes (970 bytes)



RDF clique with 4 nodes (127 bytes)

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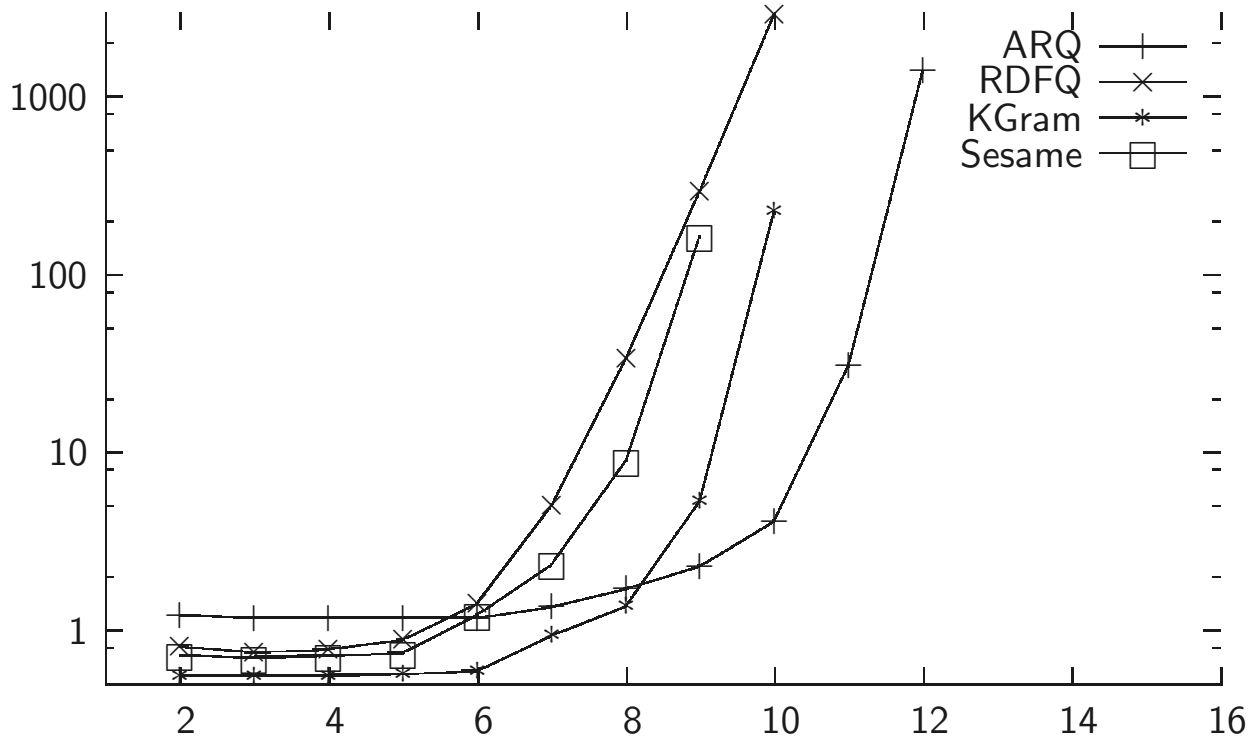


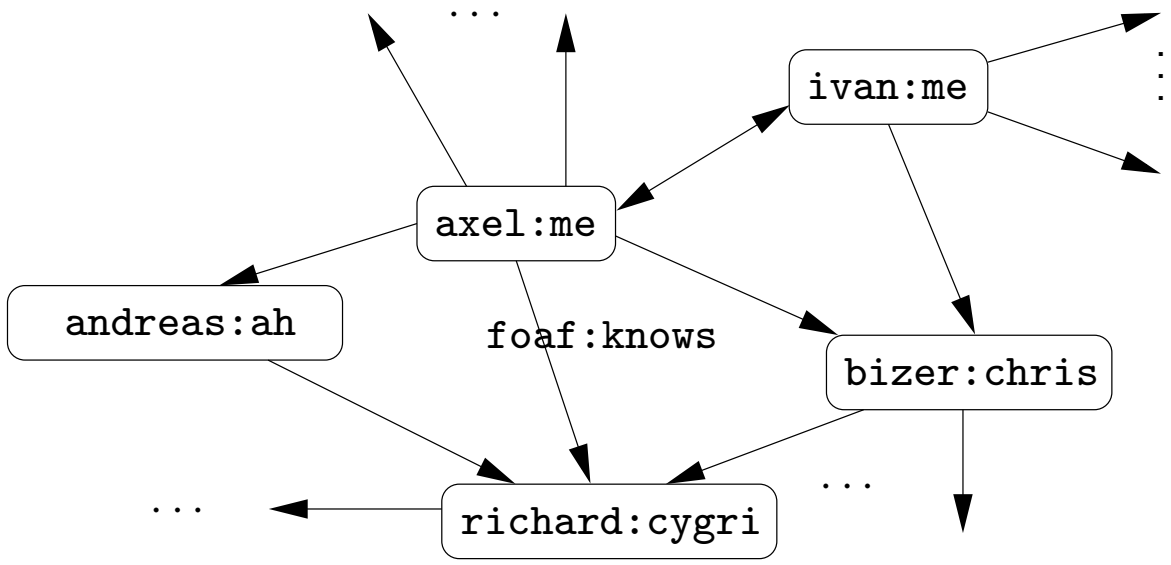
[ACP12]

```
SELECT * WHERE { :a0 (:p)* :a1 }
```

Poor performance with real Web data of small size

Data:

- Social Network data given by `foaf:knows` links
- Crawled from Axel Polleres' foaf document (3 steps)
- Different documents, deleting some nodes



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10.9KB	8.20	325.83	–	–
11.4KB	65.87	–	–	–
13.2KB	292.43	–	–	–
14.8KB	–	–	–	–
17.2KB	–	–	–	–
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[ACP12]

(time in seconds, timeout = 1hr)

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[ACP12]

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Is this a problem of these particular implementations?

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[ACP12]

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The main sources of complexity is *counting*

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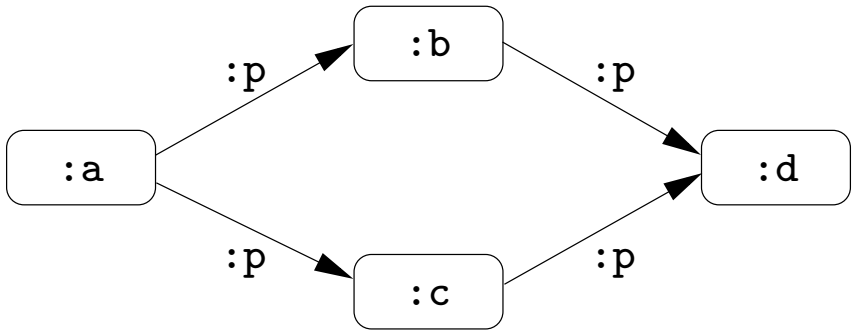
Impact on W3C standard:

- Standard semantics of SPARQL 1.1 property paths was changed in *July 2012* to overcome these issues

SPARQL 1.1 property paths match regular expressions but also *count*

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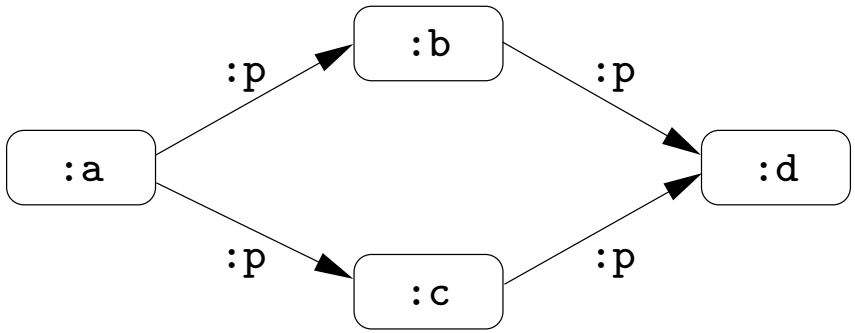


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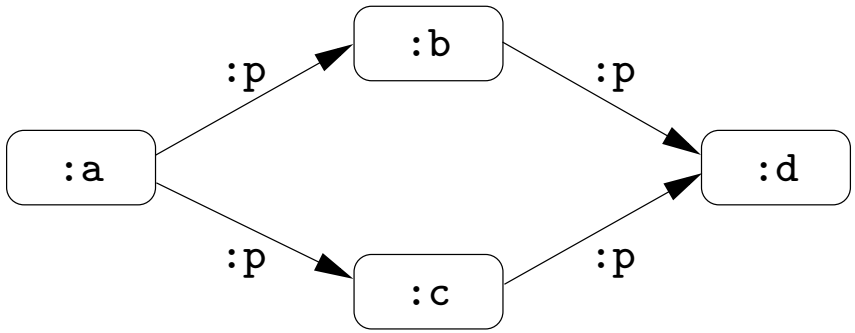


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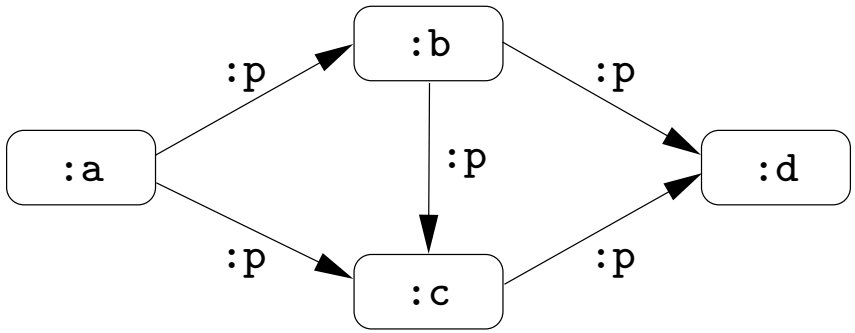


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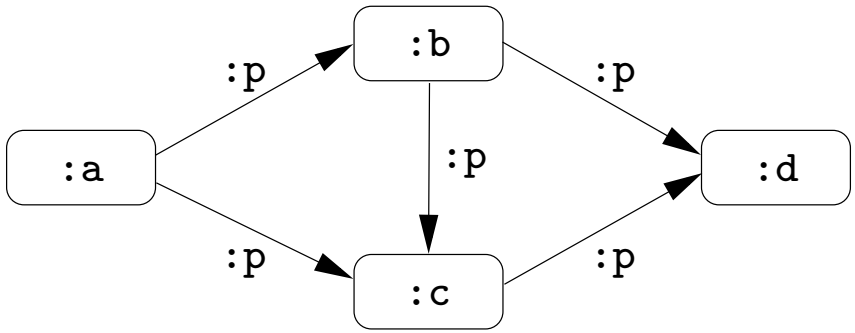


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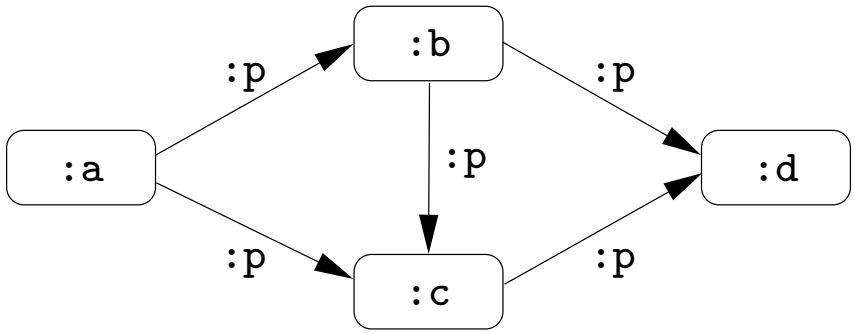


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But what if we have cycles?

SPARQL 1.1 document provides a special procedure to handle cycles (and make the count)

Evaluation of *path∗*

"the algorithm extends the multiset of results by one application of path. If a node has been visited for path, it is not a candidate for another step. A node can be visited multiple times if different paths visit it."

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SPARQL 1.1 Last Call (Jan 2012)

- W3C document provides a procedure (`ArbitraryLengthPath`)
- This procedure was formalized in [ACP12]

Counting the number of solutions...

Data: Clique of size n

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every solution is a copy of the *empty mapping* $\mu_\emptyset$ (| | in ARQ)

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Theory can help!

A bit more on complexity classes...

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- COUNTSAT is **#P**-complete

Counting problem for property paths

CountW3C

Input: RDF graph G
Property path triple $\{$ `:a` *path* `:b` $\}$

Output: Count the number of solutions of $\{$ `:a` *path* `:b` $\}$ over G
(according to the semantics proposed by W3C)

The complexity of property paths is *intractable*

Theorem (ACP12)

$\textsc{CountW3C}$ *is outside* **#P**

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Theorem (ACP12)

$\textsc{CountW3C}$ *is outside* **#P**

$\textsc{CountW3C}$ is hard to solve even if **P** = **NP**

A *doubly exponential* lower bound for counting

- Let $path_s$ be a property path of the form

$$(\cdots((:p)*)*)\cdots)*$$

with s nested stars

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In [ACP12]: A recursive formula for calculating $CountClique(s, n)$

We can explain the experimental results

CountClique(s, n) allows to *fill in the blanks*

```
{ :a0 ((:p)*)* :a1 }
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n	# Sol.
2	1
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6	–
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1 Yottabyte $>$ the estimated capacity of all digital storage in the world

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Common assumption in Databases:

- queries are much smaller than data sources

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SPARQL 1.1 query evaluation (as of January 2012) is intractable in Data Complexity

Existential semantics: a possible alternative

Possible solution

Do not count

Just check whether *there exists* a path satisfying the property path expression

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Years of experiences (theory and practice) in:

- Graph Databases
- XML
- SPARQL 1.0 (PSPARQL, Gleen)

+ equivalent regular expressions giving equivalent results

Existential semantics: decision problems

Input: RDF graph G
Property path triple $\{$ `:a` *path* `:b` $\}$

ExistsPath

Question: Is there a path from `:a` to `:b` in G satisfying the regular expression *path*?

ExistsW3C

Question: Is the number of solutions of $\{$ `:a` *path* `:b` $\}$ over G greater than 0 (according to W3C semantics)?

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Relationship between ExistsPath and ExistsW3C

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So there are possibilities for optimization

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Property path queries with `SELECT DISTINCT` can be efficiently evaluated

And we can also use `DISTINCT` over general queries

Theorem

`SELECT DISTINCT` SPARQL 1.1 queries are tractable in Data Complexity

SPARQL 1.1 implementations
do not take advantage of `SELECT DISTINCT`

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SELECT DISTINCT * WHERE { axel:me (foaf:knows)* ?x }
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Input	ARQ	RDFQ	Kgram	Sesame	Psparql	Gleen

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11.4KB	6.88	3222.47	80.73	–	0.30	1.34
13.2KB	24.42	–	394.61	–	0.31	1.38
14.8KB	–	–	–	–	0.33	1.38
17.2KB	–	–	–	–	0.35	1.42
20.5KB	–	–	–	–	0.44	1.50
25.8KB	–	–	–	–	0.45	1.52

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Optimization possibilities can remain hidden in a complicated specification

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- Paths constructed only from / and | should be counted
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- make the count (to produce copies)

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(they are not the same! consider for example `(a|a)`)

Several work to do on navigational queries for graphs!

Other lines of research with open questions:

- Nested regular expressions and nSPARQL [PAG09,BPR12]
- Queries that can output paths (e.g. ECRPQs [BLHW10])
- More complexity results on counting paths [LM12]

What is the right language (and the right semantics)
for navigating RDF graphs?

Outline

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- Can we integrate everything to effectively query Linked Data?
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A lot of work to do, so lets start! and I'm happy to collaborate! :-)

Federation and Navigation in SPARQL 1.1

Jorge Pérez

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Universidad de Chile

References

ACP12 Counting Beyond a Yottabyte ..., WWW 2012

AG08 The Expressive Power of SPARQL, ISWC 2008

BAC11 Sem & Opt of SPARQL 1.1 Federation Extensions, ISWC 2011

BLHMW10 Expressive Query Languages for Path Queries, PODS 2010

BPR12 Relative Expressiveness of Nested Regular Expressions, AMW 2012

LPSS12 Static Analysis and Optimization of SemWeb Queries, PODS 2012

LM12 Complexity of Evaluating Path Expressions in SPARQL, PODS 2012

PAG06-09 Semantics and Complexity of SPARQL, ISWC 2006, TODS 2009