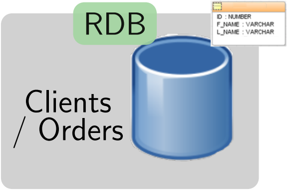
Integrating Heterogeneous Data by Extending Semantic Web Standards

Nuno Lopes

26 November, 2012

Data Integration: Pizza Delivery Company



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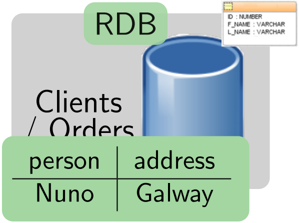
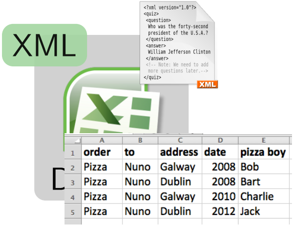


Data Integration: Pizza Delivery Company

person	address
Nuno	Galway

Data Integration: Pizza Delivery Company



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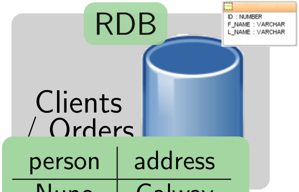

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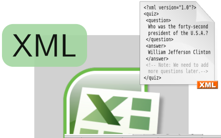

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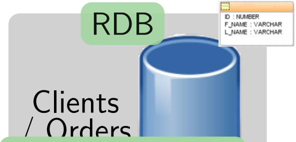

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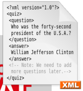
Data Integration: Pizza Delivery Company

XML

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</person>
```

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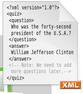

D

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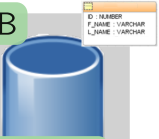
RDB



Clients / Orders

person	address
Nuno	Galway

Data Integration: Pizza Delivery Company

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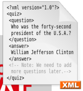


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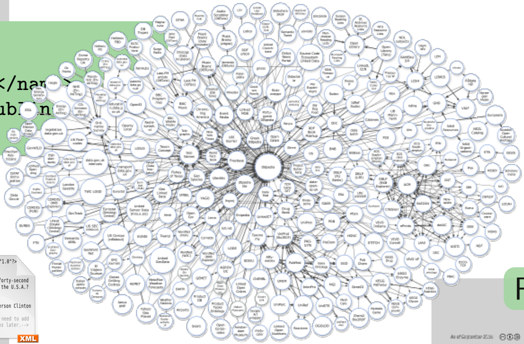

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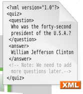

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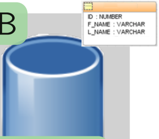

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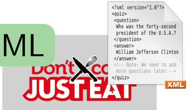


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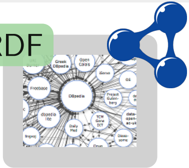

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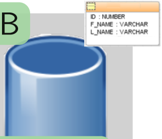

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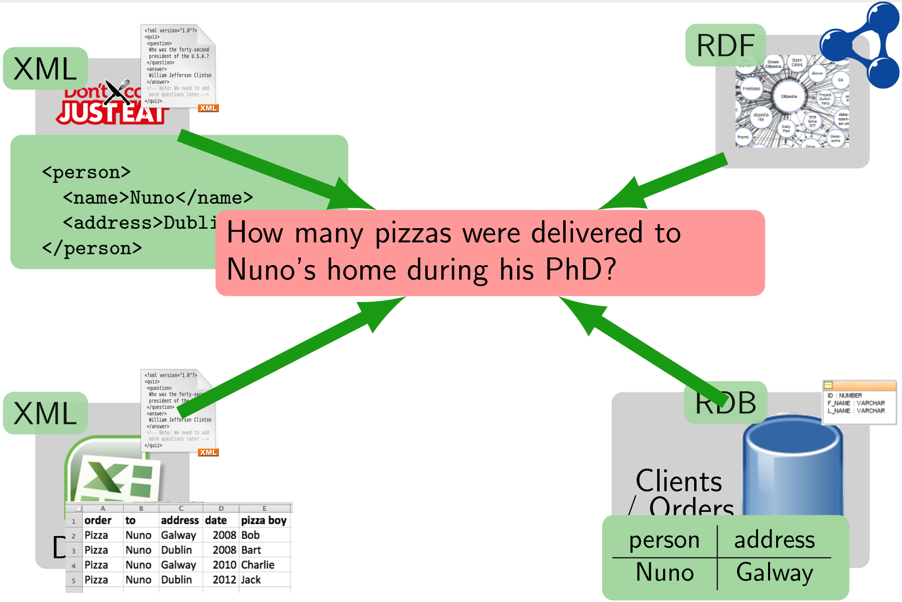

How many pizzas were delivered to Nuno's home during his PhD?

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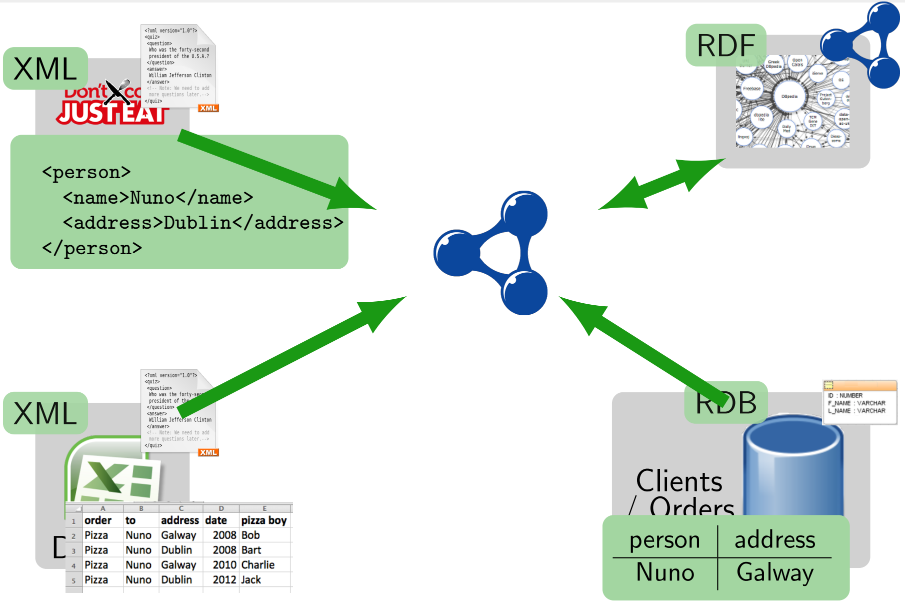

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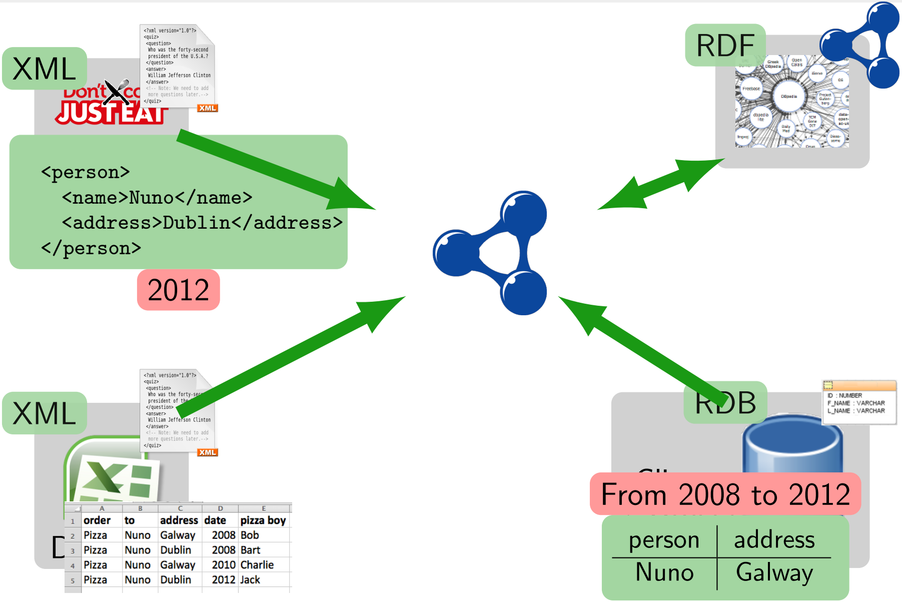

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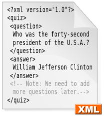
Using Query Languages for Data Integration



Using Query Languages for Data Integration

SQL

```
select address from clients
where person = "Nuno"
```

SPARQL

```
select $lat $long
from <geonames.org/..>
where { $point geo:lat $lat;
                geo:long $long }
```

XQuery

```
for $person in doc("eat.ie/..")
return $person//name
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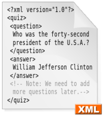

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solution sequence

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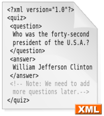
sequence of items



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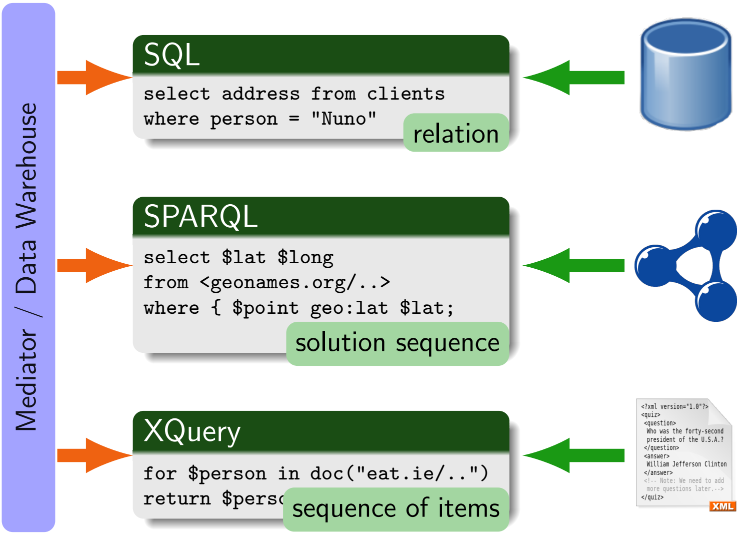

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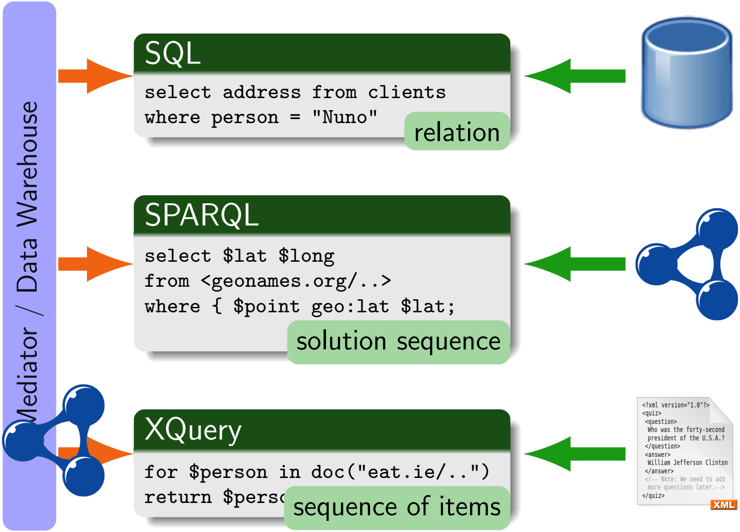

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Mediator / Data Warehouse

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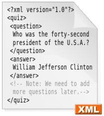

How to represent context information in RDF?

- RDF triples

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:nuno :address :Galway .
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- Domain vocabulary/ontology

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- Reification

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          rdf:predicate :address ;
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Research Questions

- How to design a query language that bridges the different formats?
- Can we reuse existing optimisations from other query languages?
- How to adapt RDF and SPARQL for context information?

Outline and Contributions

- XSPARQL
  - Syntax & Semantics
  - Implementation
  - Evaluation
- Annotated RDF(S)
  - Annotated RDF(S)
  - AnQL: Annotated SPARQL
  - Architecture

Outline and Contributions

- XSPARQL
  - Syntax & Semantics
  - Implementation
  - Evaluation

[JoDS2012], [EPIA2011]

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[AAAI2010], [ISWC2010], [JWS2012]

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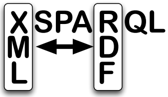
XSPARQL



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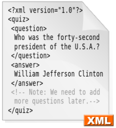
Why based on XQuery?

- Expressive language
- Use as scripting language
- Arbitrary Nesting of expressions

Same Language for each Format

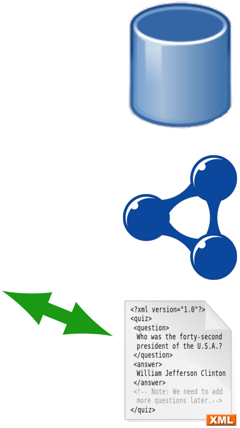


Same Language for each Format

```
for var in Expr
let var := Expr
where Expr
order by Expr
return Expr
```

XQuery

```
for $person in doc("eat.ie/..")
return $person//name
```



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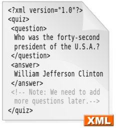
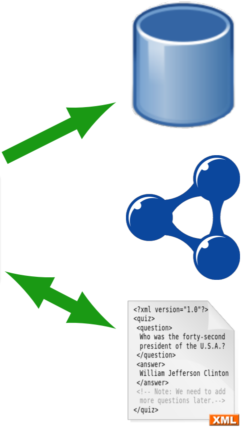


Same Language for each Format

```
for SelectSpec
from RelationList
where WhereSpecList
return Expr
```

XSPARQL

```
for address as $address from clients
where person = "Nuno"
return $address
```



Same Language for each Format

for *varlist*
from DatasetClause
where { *pattern* }
return Expr

XSPARQL

```
for $lat $long from <geonames.org/..>
where { $point geo:lat $lat;
              geo:long $long }
return $lat
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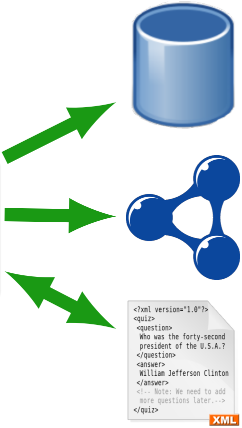

Creating RDF with XSPARQL

Convert online orders into RDF

```
prefix : <http://pizza-vocab.ie/>

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construct { :meal a :FoodOrder; :author {$person} }
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`construct` clause generates RDF

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Arbitrary XSPARQL expressions in subject, predicate, and object

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Query result

```
@prefix : <http://pizza-vocab.ie/> .

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```

Integration Query Example

"Display pizza deliveries in Google Maps using KML"

```
for $person in doc("eat.ie/...")//name
  for address as $address from clients
  where person = $person
    let $uri := fn:concat(
         "api.geonames.org/search?q=", $address)
    for $lat $long from $uri
    where { $point geo:lat $lat; geo:long $long }
    return <kml>
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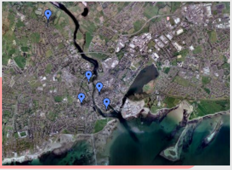

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More involved XSPARQL queries: RDB2RDF

- Direct Mapping: ∼130 LOC
- R2RML: ∼290 LOC

Language Semantics

- Extension of the XQuery Evaluation Semantics

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dynEnv.varValue ⇒ relation

person
"nuno"

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eval(SQL SELECT)

$\bowtie$ dynEnv.varValue

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dynEnv.varValue ⇒ SPARQL sol. seq.
{{ person ⇒ "nuno" }}

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eval(SPARQL SELECT)
solutions compatible
dynEnv.varValue

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$$
\frac{
\begin{array}{c}
\text{dynEnv.globalPosition} = (\mathit{Pos}_1, \cdots, \mathit{Pos}_j) \\
\text{dynEnv} \vdash \mathit{fs{:}dataset}(\mathit{DatasetClause}) \Rightarrow \mathit{Dataset} \\
\text{dynEnv} \;\vdash \mathit{fs{:}sparql}\left(\begin{array}{l}\mathit{Dataset}, \mathit{WhereClause}, \\ \mathit{SolutionModifier}\end{array}\right) \Rightarrow \mu_1, \ldots, \mu_m \\
\begin{array}{l}
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\quad + \text{varValue}\left(\begin{array}{l}\mathit{Var}_1 \Rightarrow \mathit{fs{:}value}(\mu_1, \mathit{Var}_1); \\ \ldots; \\ \mathit{Var}_n \Rightarrow \mathit{fs{:}value}(\mu_1, \mathit{Var}_n)\end{array}\right) \vdash \mathit{ExprSingle} \Rightarrow \mathit{Value}_1
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\vdots \\
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}{
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- Pushing the variable bindings into the respective query engine

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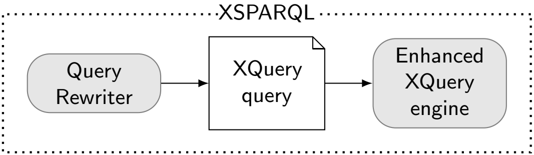

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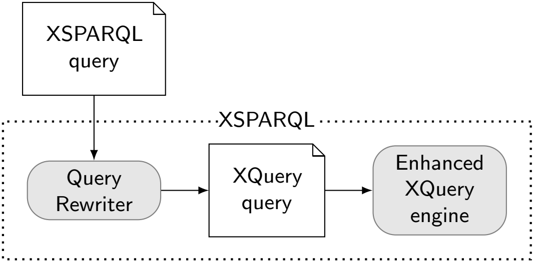

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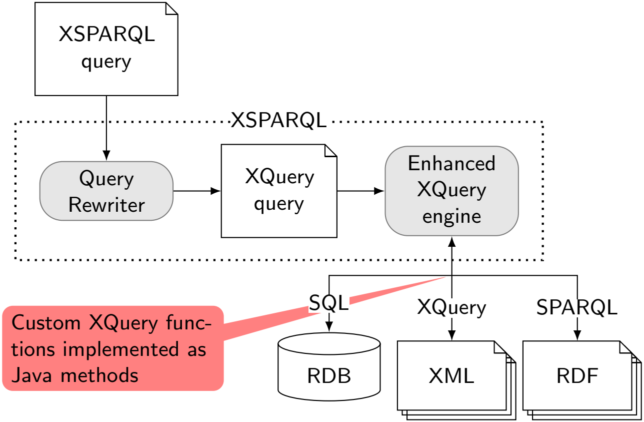

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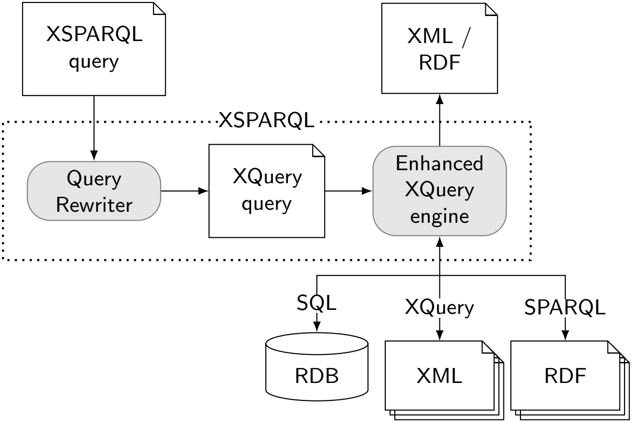
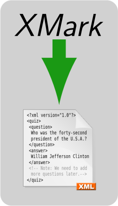


XSPARQL Evaluation



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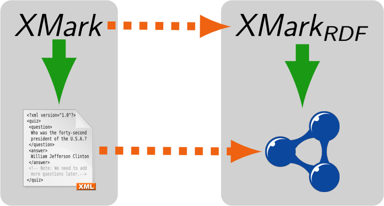

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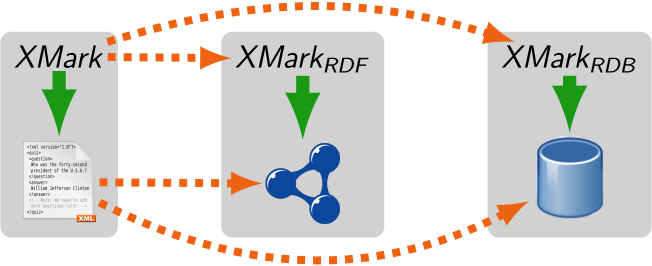

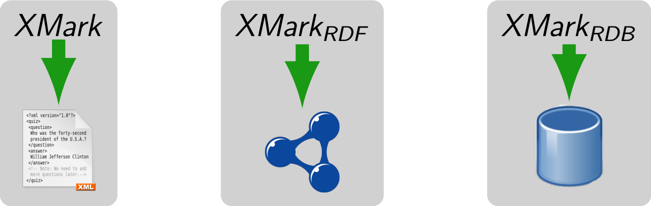

Experimental Results

- Compared to native XQuery (XMark)

  RDB and RDF: same order of magnitude for most queries

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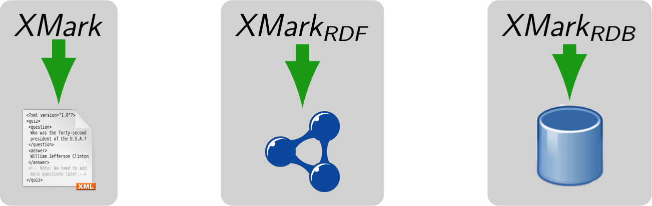

Experimental Results

- Compared to native XQuery (XMark)

  RDB and RDF: same order of magnitude for most queries
- Except on RDF nested queries (self joining data)

  several orders of magnitude slower
  due to the number of calls to the SPARQL engine

Rewriting techniques for Nested Queries

Q_8: "List the names of persons and the number of items they bought."

```
for $person $name from <input.rdf>
where { $person foaf:name $name }
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Nested Loop rewriting

Rewriting techniques for Nested Queries

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Applied to related language: SPARQL2XQuery [SAC2008]

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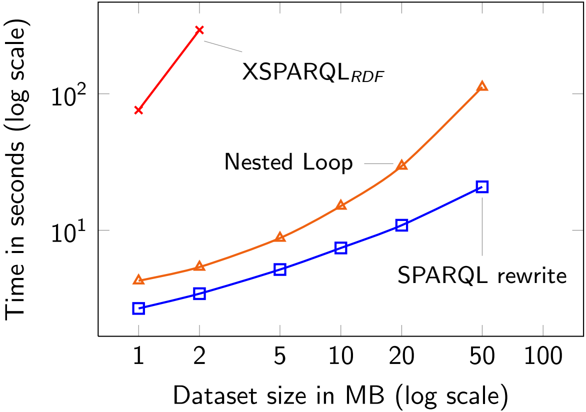
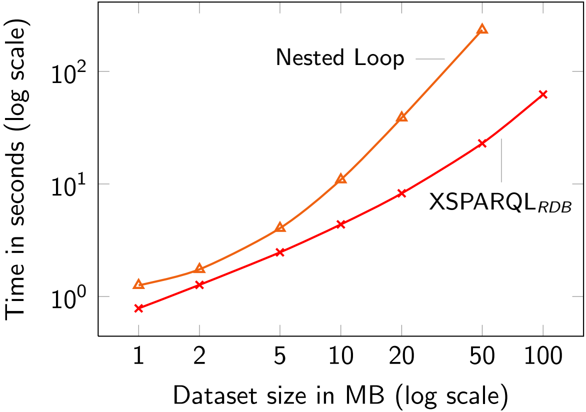
Other optimisations:
Join in SPARQL

Evaluation of different rewritings - $XMark_{RDF} Q_8$



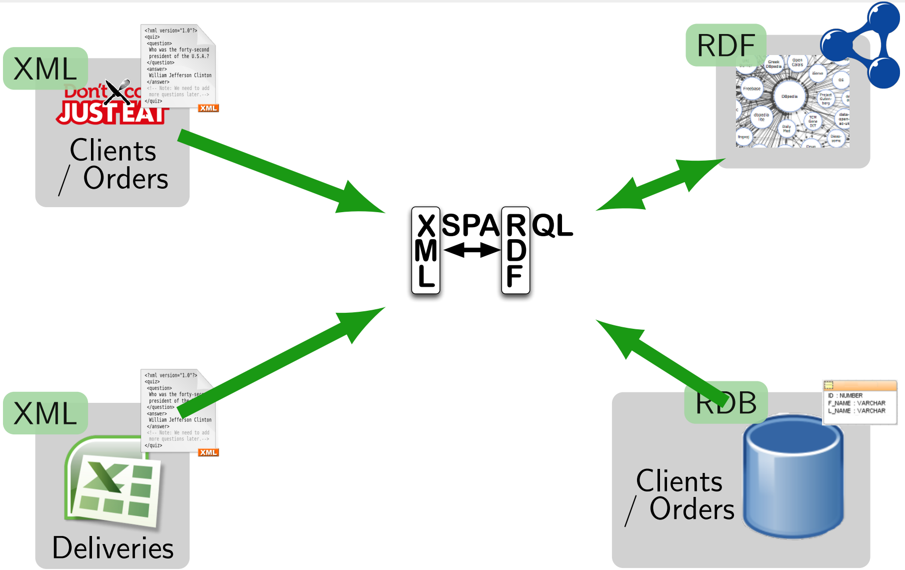
- Optimised rewritings show promising results
- Best Results: SPARQL-based
- Results included in [JoDS2012]

Evaluation of different rewritings - $XMark_{RDB}\,Q_8$



- Not so effective for RDB, requires different optimisations
- Due to schema representation?
- Additional Results for this thesis

Data Integration: Pizza Delivery Company



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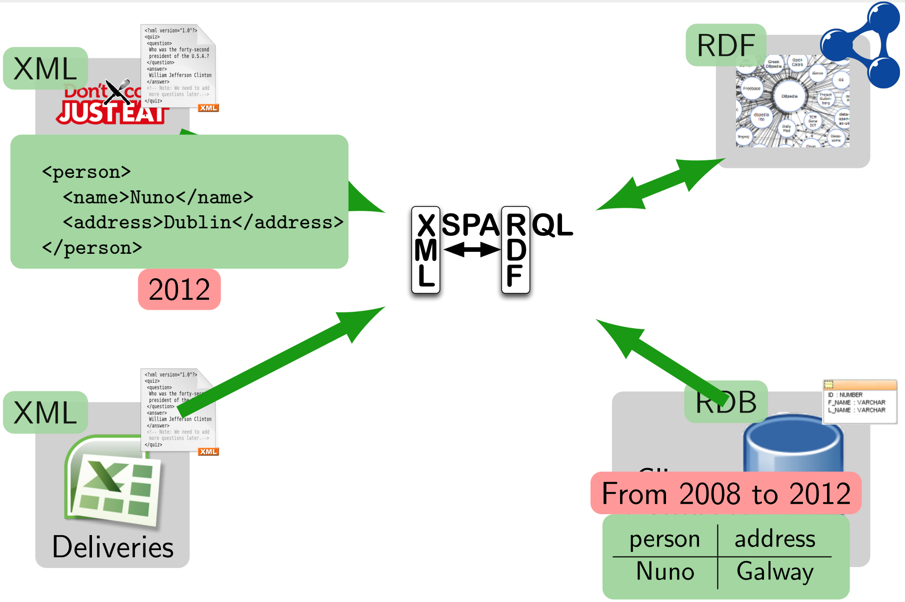

Use Annotated RDF(S)!

Annotations refer to a specific **domain**

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Temporal:

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:nuno :address :Galway .   [2008,2012]
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Representation for the values of each annotation domain

Annotated RDF(S) Inference example

Inference rules are **independent** of the annotation domain

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RDFS subPropertyOf ("sp") rule:

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```

```
   :address sp foaf:based_near .
   :nuno :address :Galway .
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   :address sp foaf:based_near .      [2009,+∞]
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	?Prop1 sp ?Prop2 .	$?v1$
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Extra rule to group annotations triples ($\oplus$):

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Operations on Annotations Elements

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$\otimes$

$[2009, 2012]$

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$$\otimes$$

$$[2009, 2012]$$

$$[]$$

Operations on Annotations Elements

$$\begin{tikzcd}
 & {[2008, +\infty]} \arrow[dl, no head] \arrow[dr, no head] \arrow[d, phantom, "\oplus"] & \\
{[2009, +\infty]} \arrow[dr, no head] & & {[2008, 2012]} \arrow[dl, no head] \\
 & {[2009, 2012]} \arrow[u, phantom, "\otimes"] \arrow[d, no head, dashed] & \\
 & {[]} &
\end{tikzcd}$$

Operations on Annotations Elements

$$\begin{tikzcd}
& {[-\infty,+\infty]} \arrow[d, dashed, no head] & \\
& {[2008,+\infty]} \arrow[dl, no head] \arrow[dr, no head] \arrow[d, phantom, "\oplus"] & \\
{[2009,+\infty]} \arrow[dr, no head] & {} \arrow[d, phantom, "\otimes"] & {[2008,2012]} \arrow[dl, no head] \\
& {[2009,2012]} \arrow[d, dashed, no head] & \\
& {[]} &
\end{tikzcd}$$

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$[2000, 2005]$ $[2008, 2012]$

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$[]$

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 & {[2000, 2005], [2008, 2012]} \arrow[dl, no head] \arrow[dr, no head] \arrow[d, phantom, "\oplus"] & \\
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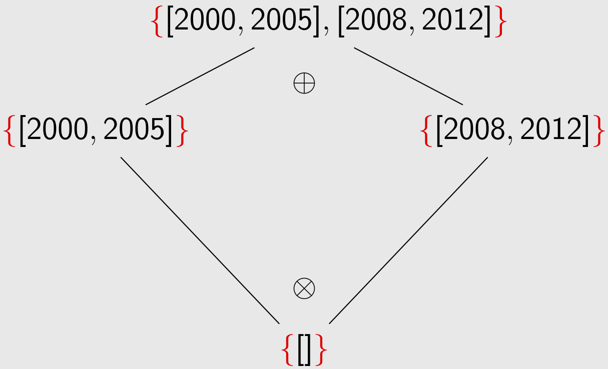

AnQL: Annotated SPARQL

Extension of SPARQL Syntax

- triple pattern

Example

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?person a foaf:Person .
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Combine BAPs using AND(.), OPTIONAL, UNION, FILTER

Evaluation of SPARQL OPTIONALs

“List my address, time interval and optionally people living in the same city at the same time.”

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SELECT   ?city ?t ?person
WHERE    { :nuno :address ?city . ?t
           OPTIONAL { ?person :address ?city . ?t } }
```

Sample input:

:nuno	:address	:Galway	.	$[2008, 2012]$
:axel	:address	:Galway	.	$[2005, 2010]$

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OPTIONAL provide more information maybe restricting annotation values

Annotated RDF(S) Domains

Temporal:

```
:nuno :address :Galway .   [2008,2012]
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Fuzzy:

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Access Control: Presented at [ICLP2012]

```
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```
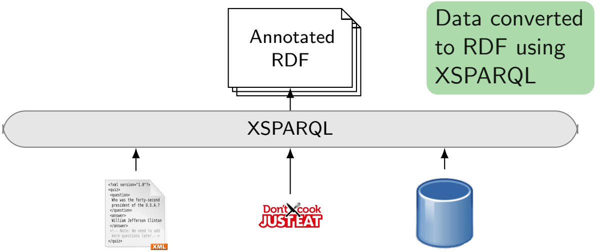
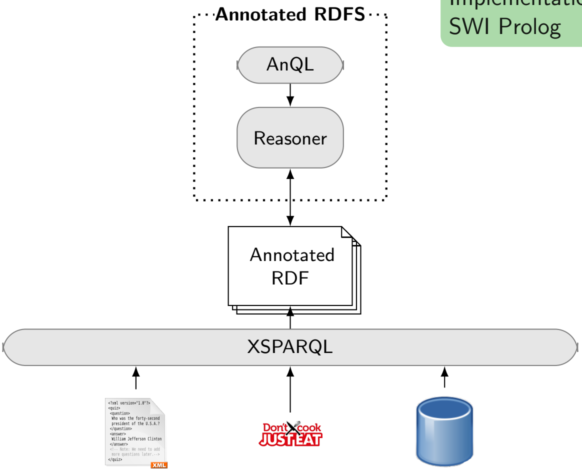

Architecture combining XSPARQL and AnQL



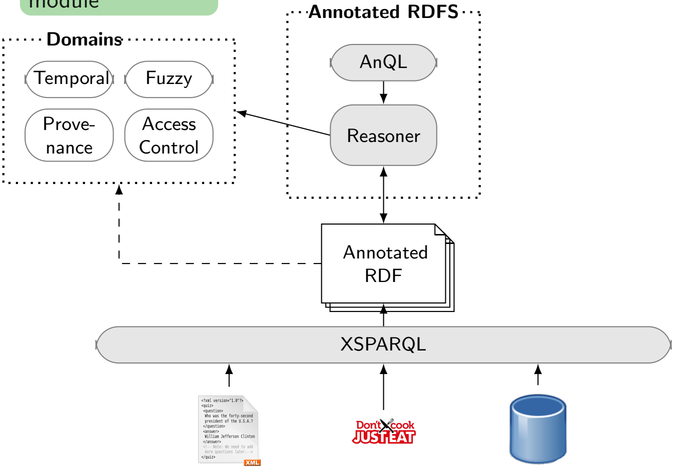
Architecture combining XSPARQL and AnQL

Implementation in SWI Prolog



Architecture combining XSPARQL and AnQL

Each domain is a different Prolog module



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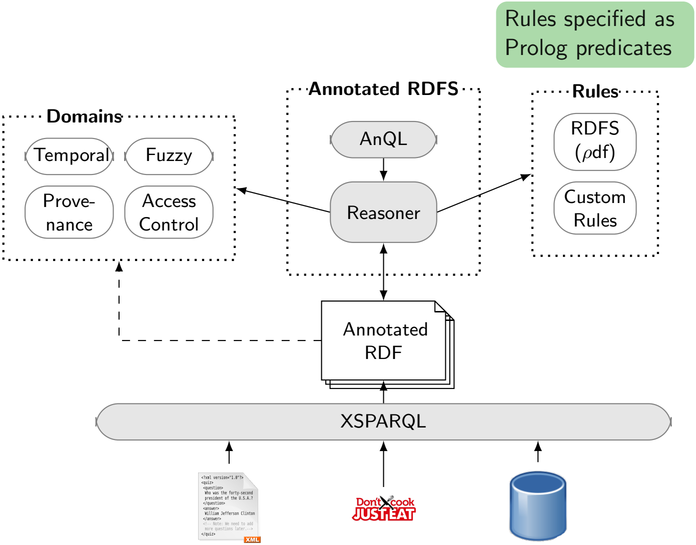

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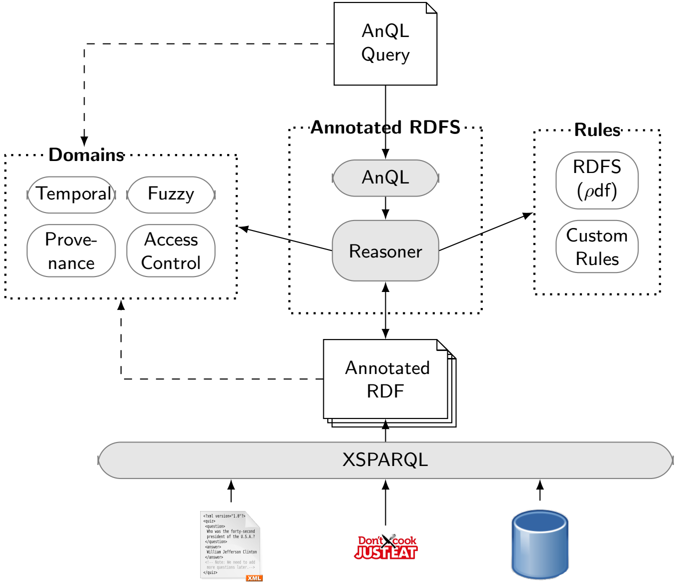

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Thank you! Questions?

Bibliography I

- Stefan Bischof, Stefan Decker, Thomas Krennwallner, Nuno Lopes, and Axel Polleres.
  Mapping between RDF and XML with XSPARQL.
  Journal on Data Semantics, 1:147–185, 2012.

- Sven Groppe, Jinghua Groppe, Volker Linnemann, Dirk Kukulenz, Nils Hoeller, and Christoph Reinke.
  Embedding SPARQL into XQuery/XSLT.
  In Roger L. Wainwright and Hisham Haddad, editors, *Proceedings of the 2008 ACM Symposium on Applied Computing (SAC), Fortaleza, Ceara, Brazil, March 16-20, 2008*, pages 2271–2278. ACM, 2008.

- Nuno Lopes, Stefan Bischof, Stefan Decker, and Axel Polleres.
  On the Semantics of Heterogeneous Querying of Relational, XML and RDF Data with XSPARQL.
  In Paulo Moura and Vitor Beires Nogueira, editors, *Proceedings of the 15th Portuguese Conference on Artificial Intelligence (EPIA2011) – Computational Logic with Applications Track*, Lisbon, Portugal, October 2011.

- Nuno Lopes, Sabrina Kirrane, Antoine Zimmermann, Axel Polleres, and Alessandra Mileo.
  A Logic Programming approach for Access Control over RDF.
  In Agostino Dovier and Vítor Santos Costa, editors, *Technical Communications of the 28th International Conference on Logic Programming (ICLP'12)*, volume 17 of *Leibniz International Proceedings in Informatics (LIPIcs)*, pages 381–392, Dagstuhl,

Germany, 2012. Schloss Dagstuhl–Leibniz-Zentrum fuer Informatik.

Nuno Lopes, Axel Polleres, Umberto Straccia, and Antoine Zimmermann.
AnQL: SPARQLing Up Annotated RDFS.
In *International Semantic Web Conference (1)*, pages 518–533, 2010.

Umberto Straccia, Nuno Lopes, Gergely Lukácsy, and Axel Polleres.
A General Framework for Representing and Reasoning with Annotated Semantic Web Data.
In Maria Fox and David Poole, editors, *Proceedings of the Twenty-Fourth AAAI Conference on Artificial Intelligence, AAAI 2010, Atlanta, Georgia, USA, July 11-15, 2010*. AAAI Press, July 2010.

Antoine Zimmermann, Nuno Lopes, Axel Polleres, and Umberto Straccia.
A General Framework for Representing, Reasoning and Querying with Annotated Semantic Web Data.
Web Semantics: Science, Services and Agents on the World Wide Web, 11(0):72–95, 2012.