Data-aware Processes: Modeling, Mining, and Verification

Part 2: Mining – Overview of OBDA

Diego Calvanese

Research Centre for Knowledge and Data (KRDB)
Free University of Bozen-Bolzano, Italy

unibz
Freie Universität Bozen
Libera Università di Bolzano
Free University of Bozen-Bolzano

3rd International Winter School on Big Data (BigDat 2017)
13–17/2/2017 – Bari, Italy

Outline

Outline

1. Motivation
   - Semantic gap
   - Solutions
2. Semantic Web standards
3. OBDA framework

Typical view of Big Data

But: data has a lot of structure

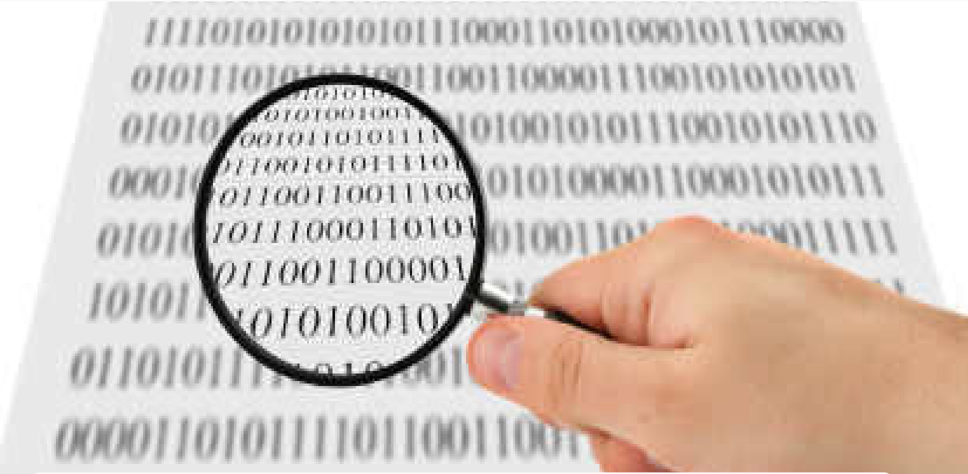
Challenge: how to use the data – Statoil Exploration

900 geologists and geophysicists in Statoil Exploration develop stratigraphic models of unexplored areas on the basis of data acquired from previous operations at nearby locations.

Data stores:

- Exploration and Production Data Store (EPDS): ∼1500 tables (100s GBs)
- OpenWorks
- Norwegian Petroleum Directorate FactPages

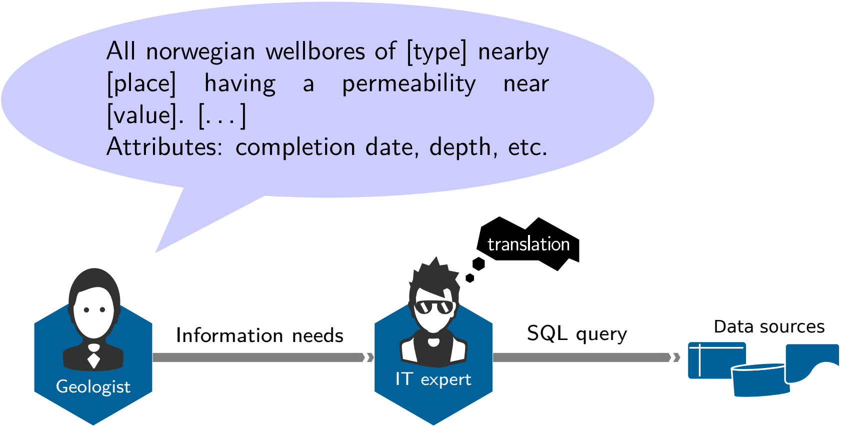
How much time is spent searching for data?



Huge problem in industry: search for data and quality assessment

E.g., in oil&gas it takes 30–70% of engineers' time (Crompton, 2008)

Designing a new (ad-hoc) query



NB: Simplified information needs

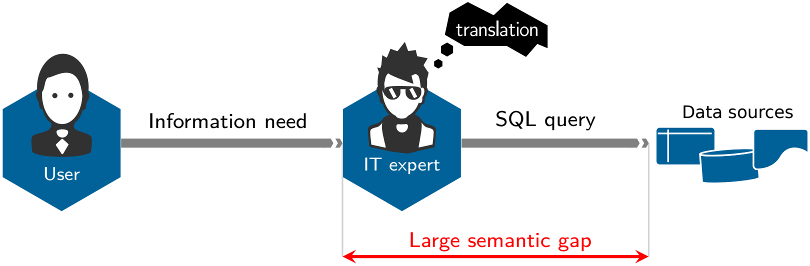
A typical query at Statoil

Anonymized extract

```
SELECT [...]
FROM
db_name.table1 table1,
db_name.table2 table2a,
db_name.table2 table2b,
db_name.table3 table3a,
db_name.table3 table3b,
db_name.table3 table3c,
db_name.table3 table3d,
db_name.table4 table4a,
db_name.table4 table4b,
db_name.table4 table4c,
db_name.table4 table4d,
db_name.table4 table4e,
db_name.table4 table4f,
db_name.table5 table5a,
db_name.table5 table5b,
db_name.table6 table6a,
db_name.table6 table6b,
db_name.table7 table7a,
db_name.table7 table7b,
db_name.table8 table8,
db_name.table9 table9,
db_name.table10 table10a,
db_name.table10 table10b,
db_name.table10 table10c,
db_name.table11 table11,
db_name.table12 table12,
db_name.table13 table13,
db_name.table14 table14,
db_name.table15 table15,
db_name.table16 table16
WHERE [...]
table2a.attr1=‘keyword’ AND
table3a.attr2=table10c.attr1 AND
table3a.attr6=table6a.attr3 AND
table3a.attr9=‘keyword’ AND
table4a.attr10 IN (‘keyword’) AND
table4a.attr1 IN (‘keyword’) AND
table5a.kinds=table4a.attr13 AND
table5b.kinds=table4c.attr74 AND
table5b.name=‘keyword’ AND
(table6a.attr19=table10c.attr17 OR
(table6a.attr2 IS NULL AND
table10c.attr4 IS NULL)) AND
table6a.attr14=table5b.attr14 AND
table6a.attr2=‘keyword’ AND
(table6b.attr14=table10c.attr8 OR
(table6b.attr4 IS NULL AND
table10c.attr7 IS NULL)) AND
table6b.attr19=table5a.attr55 AND
table6b.attr2=‘keyword’ AND
table7a.attr19=table2b.attr19 AND
table7a.attr17=table15.attr19 AND
table4b.attr11=‘keyword’ AND
table8.attr19=table7a.attr80 AND
table8.attr19=table13.attr20 AND
table8.attr4=‘keyword’ AND
table9.attr10=table16.attr11 AND
table3b.attr19=table10c.attr18 AND
table3b.attr22=table12.attr63 AND
table3b.attr66=‘keyword’ AND
table10a.attr54=table7a.attr8 AND
table10a.attr70=table10c.attr10 AND
table10a.attr16=table4d.attr11 AND
table4c.attr99=‘keyword’ AND
table4c.attr1=‘keyword’ AND
table11.attr10=table5a.attr10 AND
table11.attr40=‘keyword’ AND
table11.attr50=‘keyword’ AND
table2b.attr1=table1.attr8 AND
table2b.attr9 IN (‘keyword’) AND
table2b.attr2 LIKE ‘keyword’% AND
table12.attr9 IN (‘keyword’) AND
table7b.attr1=table2a.attr10 AND
table3c.attr13=table10c.attr1 AND
table3c.attr10=table6b.attr20 AND
table3c.attr13=‘keyword’ AND
table10b.attr16=table10a.attr7 AND
table10b.attr11=table7b.attr8 AND
table10b.attr13=table4b.attr89 AND
table13.attr1=table2b.attr10 AND
table13.attr20=’‘keyword’’ AND
table13.attr15=‘keyword’ AND
table3d.attr49=table12.attr18 AND
table3d.attr18=table10c.attr11 AND
table3d.attr14=‘keyword’ AND
table4d.attr17 IN (‘keyword’) AND
table4d.attr19 IN (‘keyword’) AND
table16.attr28=table11.attr56 AND
table16.attr16=table10b.attr78 AND
table16.attr5=table14.attr56 AND
table4e.attr34 IN (‘keyword’) AND
table4e.attr48 IN (‘keyword’) AND
table4f.attr89=table5b.attr7 AND
table4f.attr45 IN (‘keyword’) AND
table4f.attr1=‘keyword’ AND
table10c.attr2=table4e.attr19 AND
(table10c.attr78=table12.attr56 OR
(table10c.attr55 IS NULL AND
table12.attr17 IS NULL))
```

unibz

Semantic gap



Querying over tables

Requires a lot of knowledge about:

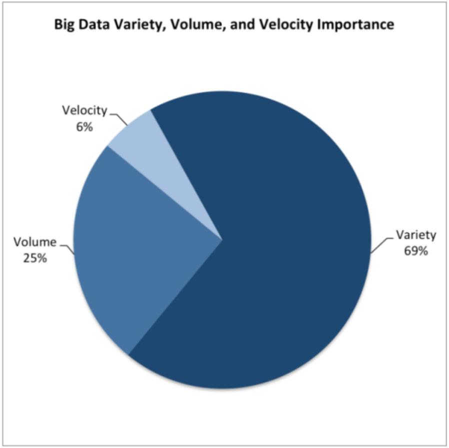
- Magic numbers
  (e.g., 1 → full professor)
- Cardinalities and normal forms
- Closely-related information spread over many tables

Data integration

- Exacerbates these issues
- Variety: **challenge #1** for most Big Data initiatives

unibz

Challenges in “Big Data” era



“Variety, Not Volume, Is Driving Big Data Initiatives”
MIT Sloan Management Review (28 March 2016)

http://sloanreview.mit.edu/article/variety-not-volume-is-driving-big-data-initiatives/

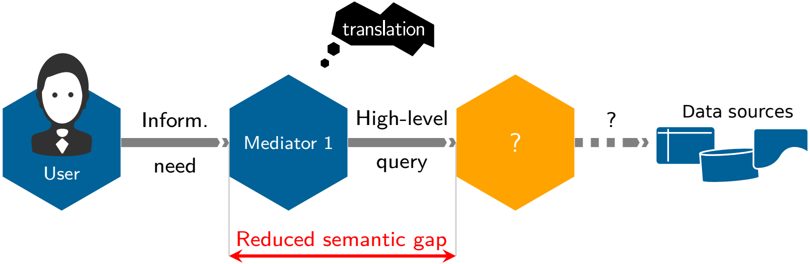
High-level translation

Main bottleneck: translation

- of the information needs
- . . . into a **formal query**

Goal

Make such a translation easy
(Ideally: IT expertise not required)

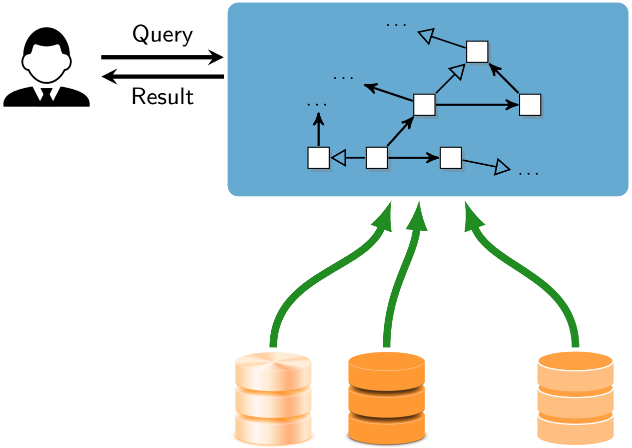


Mediator 1 could be a user, an IT expert or a GUI

General approach: two steps

1. Translate the information needs into a **high-level query**
2. Answer the high-level query **automatically**

OBDA framework



Ontology
provides global vocabulary and conceptual view

Mappings
how to populate the ontology from the data

Data Sources
external and heterogeneous

Logical transparency in accessing data:

- 👤 does not know where and how the data is stored.
- 👤 can only see a conceptual view of the data.

Outline

1. Motivation
2. Semantic Web standards
    - Resource Description Framework
    - SPARQL
    - OWL 2 QL
    - Mapping assertions
3. OBDA framework

unibz

Semantic Web standards

1. RDF (Resource Description Framework): format for Semantic Web data
2. SPARQL: query language for RDF data
3. RDFS and OWL 2 QL: ontology languages
4. Mapping languages

Resource Description Framework (RDF)

RDF provides a description of the domain in terms of **triples**:

Subject → `<http://example.org/uni2/person/3>`

Predicate → `<http://xmlns.com/foaf/0.1/firstName>`

Object → "Céline"^^xsd:string

Triple elements: resources denoted by global identifiers (IRIs)

1. Subject: IRI of the described resource
2. Predicate: IRI of the property
3. Object: attribute value or IRI of another resource

Prefixes: useful abbreviations and/or references to external information

```
@prefix foaf: <http://xmlns.com/foaf/0.1/>
@prefix : <http://example.org/voc#>
@base <http://example.org/>
```

RDF – Examples

Class membership:

Fact	Prof(*uni2/person/1*)
RDF triple	`<uni2/person/1> a :Prof`

Note: This is an abbreviation for

RDF triple	`<uni2/person/1> rdf:type :Prof`

Attribute of an individual:

Fact	lastName(*uni2/person/3*, 'Mendez')
RDF triple	`<uni2/person/3> foaf:lastName "Mendez"`

Property of an individual:

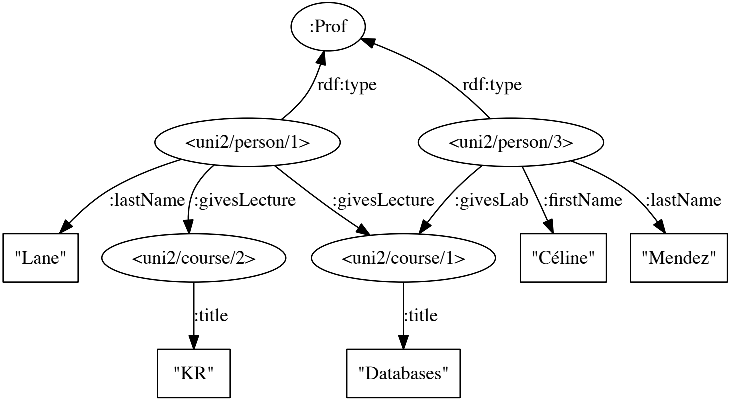
Fact	givesLab(*uni2/person/3*, *uni2/course/1*)
RDF triple	`<uni2/person/3> :givesLab <uni2/course/1>`

unibz

RDF graph – Example

```
<uni2/person/1> rdf:type :Prof
<uni2/person/1> foaf:lastName "Lane"
<uni2/person/1> :givesLecture <uni2/course/1>
...
```

We can represent such a set of facts graphically:



Additional RDF features

RDF has additional features not covered here:

- blank nodes
- named graphs

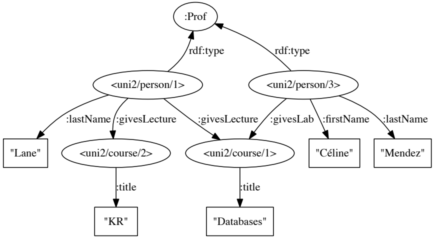
SPARQL Basic Graph Patterns

- SPARQL is the standard query language for RDF.
- **Basic Graph Pattern (BGP)**: simplest form of SPARQL query, asking for a pattern in the RDF graph

Ex.: BGP

```
SELECT ?p ?ln ?c ?t
WHERE {
  ?p :lastName ?ln .
  ?p :givesLecture ?c .
  ?c :title ?t .
}
```

When evaluated over the RDF graph



. . . the query returns:

p	ln	c	t
<uni2/person/1>	"Lane"	<uni2/course/1>	"Databases"
<uni2/person/1>	"Lane"	<uni2/course/2>	"KR"

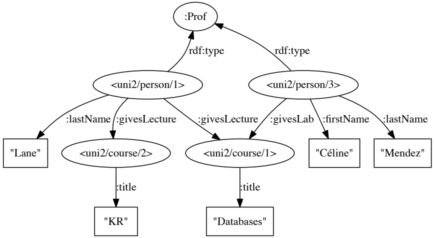
Projecting out variables in a SPARQL query

A query may also return only a subset of the variables used in the BGP.

Ex.: BGP with projection

```
SELECT ?ln ?t
WHERE {
  ?p :lastName ?ln .
  ?p :givesLecture ?c .
  ?c :title ?t .
}
```

When evaluated over the RDF graph



. . . the query returns:

ln	t
"Lane"	"Databases"
"Lane"	"KR"

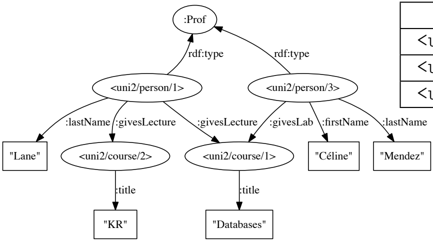
unibz

Union of Basic Graph Patterns

Ex.: BGPs with UNION

```
SELECT ?p ?ln ?c
WHERE {
  { ?p :lastName ?ln .    ?p :givesLecture ?c . }
  UNION
  { ?p :lastName ?ln .    ?p :givesLab ?c . }
}
```

When evaluated over



. . . the query returns:

p	ln	c
<uni2/person/1>	"Lane"	<uni2/course/1>
<uni2/person/1>	"Lane"	<uni2/course/2>
<uni2/person/3>	"Mendez"	<uni2/course/1>

BGPs vs. conjunctive queries

We can write queries using a more compact and abstract syntax, borrowed from database theory.

Ex.: BGP

```
SELECT ?p ?ln ?c ?t
WHERE {
  ?p :lastName ?ln .
  ?p :givesLecture ?c .
  ?c :title ?t .
}
```

vs. conjunctive query

$$\boldsymbol{q}(p, ln, c, t) \leftarrow \mathsf{lastName}(p, ln), \mathsf{givesLecture}(p, c), \mathsf{title}(c, t)$$

A **conjunctive query** $\boldsymbol{q}$ has the form $\boldsymbol{q}(\vec{x}) \leftarrow p_1(\vec{y}_1), \ldots, p(\vec{y}_k)$ where

- $\boldsymbol{q}(\vec{x})$ is called the head of $\boldsymbol{q}$,
- $p_1(\vec{y}_1), \ldots, p(\vec{y}_k)$ is a conjunction of atoms called the body of $\boldsymbol{q}$,
- all variables $\vec{x}$ in the head are among $\vec{y}_1, \ldots, \vec{y}_k$, and
- the variables in $\vec{y}_1, \ldots, \vec{y}_k$ not among $\vec{x}$ are existentially quantified.

BGPs vs. conjunctive queries (cont.)

Ex.: BGP with projection

```
SELECT ?ln ?t
WHERE {
  ?p :lastName ?ln .
  ?p :givesLecture ?c .
  ?c :title ?t .
}
```

vs. conjunctive query

$$\boldsymbol{q}(ln, t) \leftarrow \mathsf{lastName}(p, ln), \mathsf{givesLecture}(p, c), \mathsf{title}(c, t)$$

But there is a difference in semantics when we have an ontology.

SPARQL UNION vs. unions of CQs

Ex.: BGP with UNION

```
SELECT ?p ?ln ?c
WHERE {
  { ?p :lastName ?ln .
    ?p :givesLecture ?c .
  }
  UNION
  { ?p :lastName ?ln .
    ?p :givesLab ?c .
  }
}
```

vs. union of CQs (UCQ)

$$\boldsymbol{q}(p, ln, c) \leftarrow \mathsf{lastName}(p, ln), \mathsf{givesLecture}(p, c)$$

$$\boldsymbol{q}(p, ln, c) \leftarrow \mathsf{lastName}(p, ln), \mathsf{givesLab}(p, c)$$

A UCQ is written as a set of CQs, all with the same head.

unibz

The OWL 2 QL profile

- OWL 2 QL is one of the three standard profiles of OWL 2.
- Derived from the ***DL-Lite***$_{\mathcal{R}}$ description logic of the *DL-Lite*-family:
  - Groups the domain into classes of objects with common properties.
  - Binary relations between objects (object properties).
  - Binary relations from objects to values (data properties).
- Is considered a lightweight ontology language:
  - controlled expressive power
  - efficient inference
- Optimized for accessing large amounts of data (i.e., for data complexity):
  - First-order rewritability of query answering: queries over the ontology can be rewritten into SQL queries over the underlying relational database.
  - Consistency checking is also first-order rewritable.
- OWL 2 QL is equipped with a formal set-theoretic semantics.

OWL 2 QL ontologies

- An OWL 2 QL ontology $\langle \mathcal{T}, \mathcal{A} \rangle$ is constituted by:
  - a TBox $\mathcal{T}$, modeling the intensional level information (i.e., axioms), and
  - an ABox $\mathcal{A}$, modeling the extensional level information (i.e., facts).
- In the OBDA setting, the ABox is (usually) implicitly defined through the database and mappings.
- Therefore, in the following, we use the term "ontology" to refer to the TBox only.

Constructs of OWL 2 QL/ *DL-Lite*$_{\mathcal{R}}$

- Class hierarchies: `rdfs:subClassOf`
- Property hierarchies: `rdfs:subPropertyOf`
- Property domain: `rdfs:domain`
- Property range: `rdfs:range`
- Inverse properties: `owl:inverseOf`
- Class disjointness: `owl:disjointWith`
- Mandatory participation: `owl:someValuesFrom` in superclass expression

RDF Schema (RDFS)

rdfs:subClassOf ($A \sqsubseteq B$)

```
:FullProf rdfs:subClassOf :Professor .
<uni1/academic/1> a :FullProf .
```
$\Longrightarrow$ `<uni1/academic/1> a :Professor .`

rdfs:subPropertyOf ($P \sqsubseteq R$)

```
:givesLecture rdfs:subPropertyOf :teaches .
<uni2/academic/2> :givesLecture <uni2/course/1> .
```
$\Longrightarrow$ `<uni2/academic/2> :teaches <uni2/course/1> .`

rdfs:domain ($\exists P \sqsubseteq A$)

```
:teaches rdfs:domain :Teacher .
<uni2/academic/2> :teaches <uni2/course/1> .
```
$\Longrightarrow$ `<uni2/academic/2> a :Teacher .`

rdfs:range ($\exists P^{-} \sqsubseteq A$)

```
:teaches rdfs:range :Course .
<uni2/academic/2> :teaches <uni2/course/1> .
```
$\Longrightarrow$ `<uni2/course/1> a :Course .`

unibz

Other constructs of OWL 2 QL I

owl:inverseOf $(P^- \sqsubseteq R,\ R^- \sqsubseteq P)$

```
:isTaughtBy owl:inverseOf :teaches .
<uni2/academic/2> :teaches <uni2/course/1> .
```
```
⟹   <uni2/course/1> :isTaughtBy <uni2/academic/2> .
```

owl:someValuesFrom in the superclass expression $(A \sqsubseteq \exists R.B)$

```
:GraduateStudent rdfs:subClassOf
   [ a owl:Restriction ;
     owl:onProperty :isSupervisedBy ;
     owl:someValuesFrom :Professor ] .
<uni2/person/10> a :GraduateStudent .
```
```
      <uni2/person/10> a
        [ a owl:Restriction ;
⟹         owl:onProperty :isSupervisedBy ;
          owl:someValuesFrom :Professor ] .
```

Other constructs of OWL 2 QL II

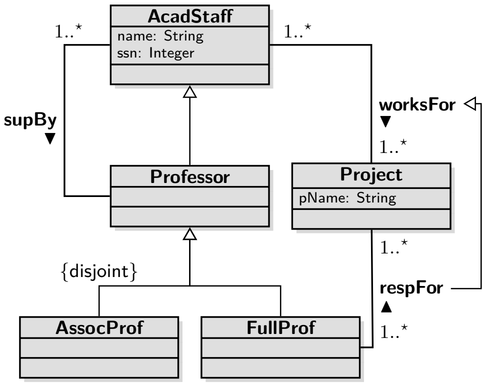
owl:disjointWith $(A \sqsubseteq \neg B,\ B \sqsubseteq \neg A)$

```
:Student owl:disjointWith :Professor .
<uni1/academic/19> a :Professor .
<uni1/academic/19> a :Student .
```

$\Longrightarrow$ Inconsistent RDF graph

unibz

Capturing UML class diagrams/ER schemas in *DL-Lite*$_\mathcal{R}$



$$
\begin{array}{rcl}
\mathsf{Professor} & \sqsubseteq & \mathsf{AcadStaff} \\
\mathsf{AssocProf} & \sqsubseteq & \mathsf{Professor} \\
\mathsf{FullProf} & \sqsubseteq & \mathsf{Professor} \\
\mathsf{AssocProf} & \sqsubseteq & \neg\mathsf{FullProf} \\
\mathsf{AcadStaff} & \sqsubseteq & \exists \mathsf{ssn} \\
\exists \mathsf{ssn} & \sqsubseteq & \mathsf{AcadStaff} \\
\exists \mathsf{ssn}^- & \sqsubseteq & \mathtt{Integer} \\
\exists \mathsf{worksFor} & \sqsubseteq & \mathsf{AcadStaff} \\
\exists \mathsf{worksFor}^- & \sqsubseteq & \mathsf{Project} \\
\mathsf{AcadStaff} & \sqsubseteq & \exists \mathsf{worksFor} \\
\mathsf{Project} & \sqsubseteq & \exists \mathsf{worksFor}^- \\
\mathsf{respFor} & \sqsubseteq & \mathsf{worksFor} \\
 & \vdots &
\end{array}
$$

DL-Lite$_\mathcal{R}$ / OWL 2 QL **cannot capture**:

- covering constraints – This would require **disjunction**
- identity between individuals – This would `owl:sameAs` – see later
- functionality of roles – This would require number restrictions

unibz

DL-Lite$_\mathcal{R}$ captures conceptual modeling formalisms

Modeling construct	*DL-Lite*	FOL formalization
ISA on classes	$A_1 \sqsubseteq A_2$	$\forall x(A_1(x) \rightarrow A_2(x))$
. . . and on relations	$R_1 \sqsubseteq R_2$	$\forall x, y(R_1(x,y) \rightarrow R_2(x,y))$
Disjointness of classes	$A_1 \sqsubseteq \neg A_2$	$\forall x(A_1(x) \rightarrow \neg A_2(x))$
. . . and of relations	$R_1 \sqsubseteq \neg R_2$	$\forall x, y(R_1(x,y) \rightarrow \neg R_2(x,y))$
Domain of relations	$\exists P \sqsubseteq A_1$	$\forall x(\exists y(P(x,y)) \rightarrow A_1(x))$
Range of relations	$\exists P^- \sqsubseteq A_2$	$\forall x(\exists y(P(y,x)) \rightarrow A_2(x))$
Mandatory participation *(min card = 1)*	$A_1 \sqsubseteq \exists P$ $A_2 \sqsubseteq \exists P^-$	$\forall x(A_1(x) \rightarrow \exists y(P(x,y)))$ $\forall x(A_2(x) \rightarrow \exists y(P(y,x)))$
. . .	. . .	. . .

unibz

Mapping assertions – RDB-RDF

Global-As-View (GAV) mapping assertion $\varphi \rightsquigarrow \psi$

- φ: FO query (over DB predicates)
- ψ: atom (over an RDF predicate)
- Open-World Assumption (by default)

Class instance (`:Student`)

Source	$\boldsymbol{q}(s) \leftarrow \texttt{uni1-student}(s, f, l)$
	
	`SELECT s_id`
	`FROM uni1.student`

Target	$\text{Student}(\text{URI}_1(s))$ `ex:uni1/student/{s_id} a :Student .`

unibz

Mapping assertions RDB-RDF

Ontop native format (similar to the R2RML standard)

Data property (`foaf:firstName`)

Source (SQL)	`SELECT s_id, firstName, lastName FROM uni1.student`
Target (RDF)	`ex:uni1/student/{s_id} foaf:firstName "{firstName}"^^xsd:string ; foaf:lastName "{lastName}"^^xsd:string .`

Object property (`:teaches`)

Source	`SELECT * FROM "uni1"."teaching"`
Target (RDF)	`ex:uni1/academic/{a_id} :teaches ex:uni1/course/{c_id} .`

Magic number

Source	`SELECT * FROM "uni1"."academic" WHERE "position" = 1`
Target (RDF)	`ex:uni1/academic/{a_id} a :FullProf .`

Outline

Ontology-based data access: Formalization

To formalize OBDA, we distinguish between the intensional and the extensional level information.

An **OBDA specification** is a triple $\mathcal{P} = \langle \mathcal{T}, \mathcal{S}, \mathcal{M} \rangle$, where:

- $\mathcal{T}$ is the intensional level of an ontology.
  We consider ontologies formalized in description logics (DLs), hence the intensional level is a DL TBox.
- $\mathcal{S}$ is a (possibly federated) relational database schema for the data source(s), possibly with constraints;
- $\mathcal{M}$ is a set of mapping assertions between $\mathcal{T}$ and $\mathcal{S}$.

An **OBDA instance** is a pair $\mathcal{O} = \langle \mathcal{P}, \mathcal{D} \rangle$, where

- $\mathcal{P} = \langle \mathcal{T}, \mathcal{S}, \mathcal{M} \rangle$ is an OBDA specification, and
- $\mathcal{D}$ is a relational database compliant with $\mathcal{S}$.

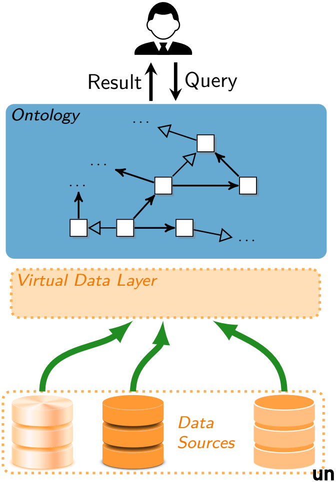
Semantics of OBDA: Intuition

In an OBDA instance $\mathcal{O} = \langle\langle\mathcal{T}, \mathcal{M}, \mathcal{S}\rangle, \mathcal{D}\rangle$, the **mapping** $\mathcal{M}$ encodes how the data $\mathcal{D}$ in the source(s) $\mathcal{S}$ should be used to populate the elements of $\mathcal{T}$.

Virtual data layer

The data $\mathcal{D}$ and the mapping $\mathcal{M}$ define a virtual data layer $\mathcal{V} = \mathcal{M}(\mathcal{D})$

- Queries are answered w.r.t. $\mathcal{T}$ and $\mathcal{V}$.
- We do not really materialize the data of $\mathcal{V}$ (it is virtual!).
- Instead, the intensional information in $\mathcal{T}$ and $\mathcal{M}$ is used to translate queries over $\mathcal{T}$ into queries formulated over $\mathcal{S}$.



unibz

Semantics of mappings

To formally define the semantics of an OBDA instance $\mathcal{O} = \langle \mathcal{P}, \mathcal{D} \rangle$, where $\mathcal{P} = \langle \mathcal{T}, \mathcal{S}, \mathcal{M} \rangle$, we first need to define the semantics of mappings.

Satisfaction of a mapping assertion with respect to a database

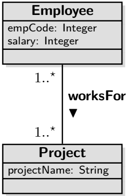
An interpretation $\mathcal{I}$ **satisfies** a mapping assertion $\Phi(\vec{x}) \rightsquigarrow \Psi(\vec{x})$ in $\mathcal{M}$ **with respect to a database** $\mathcal{D}$ **for** $\mathcal{S}$, if the following FOL sentence is true in $\mathcal{I} \cup \mathcal{D}$:

$$\forall \vec{x}.\, \Phi(\vec{x}) \rightarrow \Psi(\vec{x})$$

Intuitively, $\mathcal{I}$ **satisfies** $\Phi \rightsquigarrow \Psi$ w.r.t. $\mathcal{D}$ if all facts obtained by evaluating Φ over $\mathcal{D}$ and then propagating the answers to Ψ, hold in $\mathcal{I}$.

unibz

Semantics of mappings – Example



D_1:

SSN	*PrName*
23AB	optique
...	...

D_2:

Code	*Salary*
e23	1500
...	...

D_3:

Code	*SSN*
e23	23AB
...	...

The following interpretation $\mathcal{I}$ satisfies the mapping assertions m_1 and m_2 with respect to the above database:

$\mathcal{I} : \Delta_O^{\mathcal{I}} = \{\textbf{pers}(\texttt{23AB}), \textbf{proj}(\texttt{optique}), \ldots\}, \quad \Delta_V^{\mathcal{I}} = \{\texttt{optique}, \texttt{1500}, \ldots\}$

$\mathsf{Employee}^{\mathcal{I}} = \{\textbf{pers}(\texttt{23AB}), \ldots\}, \quad \mathsf{Project}^{\mathcal{I}} = \{\textbf{proj}(\texttt{optique}), \ldots\},$

$\mathsf{projectName}^{\mathcal{I}} = \{(\textbf{proj}(\texttt{optique}), \texttt{optique}), \ldots\},$

$\mathsf{worksFor}^{\mathcal{I}} = \{(\textbf{pers}(\texttt{23AB}), \textbf{proj}(\texttt{optique})), \ldots\},$

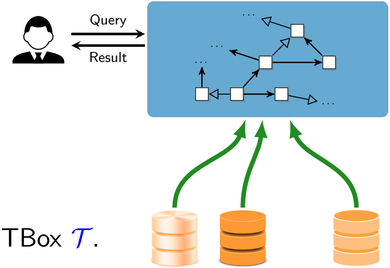
$\mathsf{salary}^{\mathcal{I}} = \{(\textbf{pers}(\texttt{23AB}), \texttt{1500}), \ldots\}$

m_1:
```
SELECT SSN, PrName
FROM D1
```
$\rightsquigarrow$ Employee(**pers**(*SSN*)), Project(**proj**(*PrName*)), projectName(**proj**(*PrName*), *PrName*), worksFor(**pers**(*SSN*), **proj**(*PrName*))

m_2:
```
SELECT SSN, Salary
FROM D2, D3
WHERE D2.Code = D3.Code
```
$\rightsquigarrow$ Employee(**pers**(*SSN*)), salary(**pers**(*SSN*), *Salary*)

unibz

Semantics of an OBDA instance



Let $\mathcal{I} = (\Delta^{\mathcal{I}}, \cdot^{\mathcal{I}})$ be an interpretation of the TBox $\mathcal{T}$.

Model of an OBDA instance

$\mathcal{I}$ is a **model** of $\mathcal{O} = \langle \mathcal{P}, \mathcal{D} \rangle$, with $\mathcal{P} = \langle \mathcal{T}, \mathcal{S}, \mathcal{M} \rangle$ if:

- $\mathcal{I}$ is a model of $\mathcal{T}$, and
- $\mathcal{I}$ satisfies $\mathcal{M}$ w.r.t. $\mathcal{D}$, i.e., it satisfies every assertion in $\mathcal{M}$ w.r.t. $\mathcal{D}$.

An OBDA instance $\mathcal{O}$ is **satisfiable** if it admits at least one model.

Query answering in OBDA

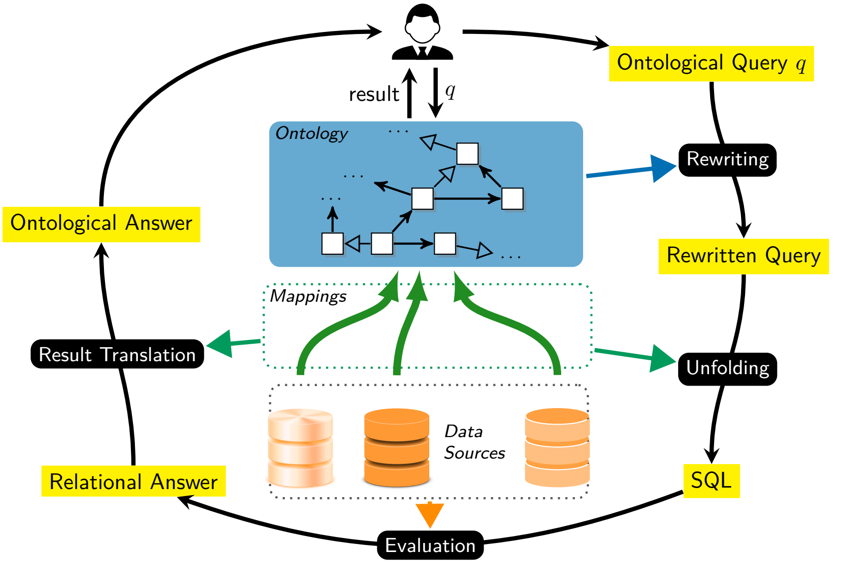
In OBDA, we are interested in answering queries formulated over the TBox, using the data provided from the database through the mapping.

Formally:

- An OBDA instance $\mathcal{O} = \langle \mathcal{P}, \mathcal{D} \rangle$, with $\mathcal{P} = \langle \mathcal{T}, \mathcal{S}, \mathcal{M} \rangle$ has multiple models.
- We are interested in the answers to queries that hold in all models $\mathcal{I}$ of $\mathcal{O}$: **certain answers**

unibz

Query answering by rewriting (conceptual framework)



Ontop

- State-of-the-art OBDA system
- Compliant with the RDFS, OWL 2 QL, R2RML, and SPARQL standards.
- Supports all major relational DBs
  - Oracle, DB2, MS SQL Server, Postgres, MySQL, Teiid, Exareme, etc.
- Open-source and released under Apache 2 license
- Development of *Ontop*:
  - development started in 2009
  - already well established:
    - +200 members in the mailing list
    - +7000 downloads in last 18 months
  - main development carried out in the context of the EU project Optique

References I

[1] Elena Botoeva, Diego Calvanese, Benjamin Cogrel, Martin Rezk, and Guohui Xiao. "OBDA Beyond Relational DBs: A Study for MongoDB". In: *Proc. of the 29th Int. Workshop on Description Logics (DL)*. 2016.

[2] Elena Botoeva, Diego Calvanese, Valerio Santarelli, Domenico F. Savo, Alessandro Solimando, and Guohui Xiao. "Beyond OWL 2 QL in OBDA: Rewritings and Approximations". In: *Proc. of the 30th AAAI Conf. on Artificial Intelligence (AAAI)*. 2016.

[3] Guohui Xiao, Martin Rezk, Mariano Rodriguez-Muro, and Diego Calvanese. "Rules and Ontology Based Data Access". In: *Proc. of the 8th Int. Conf. on Web Reasoning and Rule Systems (RR)*. Vol. 8741. Lecture Notes in Computer Science. Springer, 2014, pp. 157–172.

[4] Diego Calvanese, Martin Giese, Dag Hovland, and Martin Rezk. "Ontology-based Integration of Cross-linked Datasets". In: *Proc. of the 14th Int. Semantic Web Conf. (ISWC)*. Vol. 9366. Lecture Notes in Computer Science. Springer, 2015, pp. 199–216.