UNIVERSITÄT ZU LÜBECK
INSTITUT FÜR INFORMATIONSSYSTEME

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Ontology-Based Data Access

Lecture 8: DL-Lite,Rewriting, Unfolding

13 January, 2016

Foundations of Ontologies and Databases for Information Systems

CS5130 (Winter 2015)

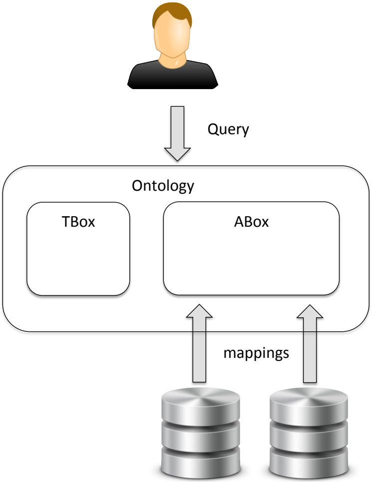
Recap of Lecture 7

Ontology-Based Data Access

- Use ontologies as interface

  ...
- to access (here: query)
- data stored in some format

  ...
- using mappings



- Talked about description logics as ontology representation language
- Semantics + Tableaux Calculus

References

- Reasoning Web Summer School 2014 course by Kontchakov on Description Logics

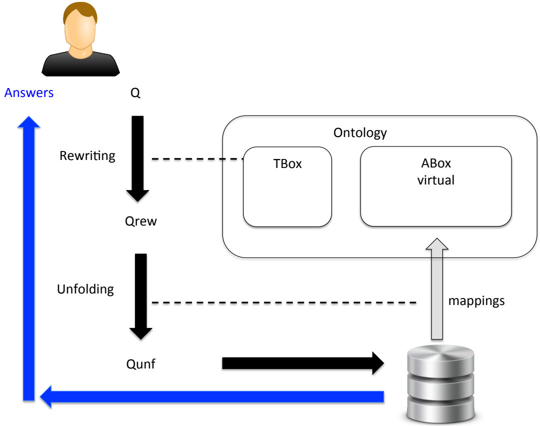
  http://rw2014.di.uoa.gr/sites/default/files/slides/An_Introduction_to_Description_Logics.pdf
- Lecture notes by Calvanese in 2013/2014 course on Ontology and Database Systems

  https://www.inf.unibz.it/~calvanese/teaching/14-15-odbs/lecture-notes/
- Parts of Reasoning Web Summer School 2014 course by Ö. on Ontology-Based Data Access on Temporal and Streaming Data

  http://rw2014.di.uoa.gr/sites/default/files/slides/Ontology_Based_Data_Access_on_Temporal_and_Streaming_Data.pdf

OBDA in the Classical Sense

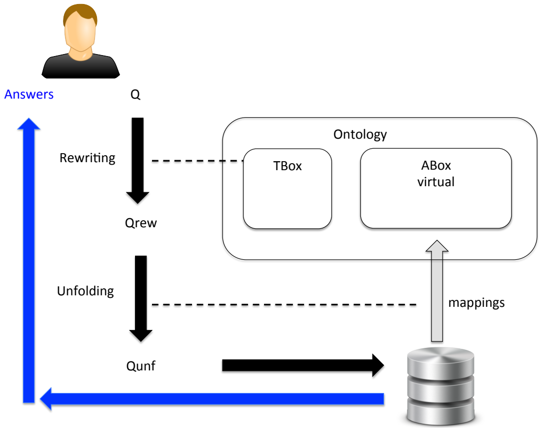
- Keep the data where they are because of large volume
- ABox not loaded into main memory, kept virtual



Rewriting

OBDA in the Classical Sense

- Query answering not with deduction but rewriting and unfolding
- Challenge: Complete and correct rewriting and unfolding



Formal Notion of Rewriting

- Rewriting informally: Can produce for a TBox and query a new query that gives exactly the certain answers for any ABox

Definition

For any ontology language $\mathcal{L}_\mathcal{T}$ and query language $\mathcal{L}_{Qry}$, answering queries from $\mathcal{L}_{\mathcal{O}-Q}$ is $\mathcal{L}_{\mathcal{A}-Q}$-**rewritable** iff for every TBox $\mathcal{T}$ over $\mathcal{L}_\mathcal{T}$ and query Q in $\mathcal{L}_{\mathcal{O}-Q}$ there is a query Q_{rew} in $\mathcal{L}_{\mathcal{A}-Q}$ such that

$$cert(Q, (Sig, \mathcal{T}, \mathcal{A})) = cert(Q_{rew}, \mathcal{A})$$

- Computing $cert(Q_{rew}, \mathcal{A})$ is easy as the models of $\mathcal{A}$ are all similar
- It is enough to consider minimal Herbrand model $DB(\mathcal{A})$:

$$cert(Q_{rew}, \mathcal{A}) = Q_{rew}(DB(\mathcal{A}))$$

Rewriting for Different Languages

- Possibility of rewriting depends on right expressivity balance between $\mathcal{L}_{\mathcal{T}}$, $\mathcal{L}_{\mathcal{O}-Q}$, $\mathcal{L}_{\mathcal{A}-Q}$.
- One aims at computably feasible $\mathcal{L}_{\mathcal{A}-Q}$ queries
- In classical OBDA
  - $\mathcal{L}_{\mathcal{T}}$: Language of the DL-Lite family
  - $\mathcal{L}_{\mathcal{O}-Q}$: Unions of conjunctive queries
  - $\mathcal{L}_{\mathcal{A}-Q}$: (Safe) FOL/SQL (in AC^0)

DL-Lite

DL-Lite

- Family of DLs underlying the OWL 2 QL profile
- Tailored towards the classical OBDA scenario
  - Captures (a large fragment of) UML
  - FOL-rewritability for ontology satisfiability checking and query answerings for UCQs
  - Used in many implementations of OBDA (QuOnto, Presto, Rapid, Nyaya, ontop etc.)
- We give a rough overview. For details consult, e.g.,

  Lit: Calvanese et al. Ontologies and databases: The DL-Lite approach. In Tessaris/Franconi, editors, Semantic Technologies for Informations Systems. 5th Int. Reasoning Web Summer School (RW 2009), pages 255–356. Springer, 2009.

  Lit: A. Artale, D. Calvanese, R. Kontchakov, and M. Zakharyaschev. The DL-Lite family and relations. J. Artif. Intell. Res. (JAIR), 36:1–69, 2009.

DL-Lite$_\mathcal{F}$

- Simple member of the family allowing functional constraints

- Syntax
  - Basic role $Q ::= P \mid P^-$ for $P \in N_R$
  - Roles: $R ::= Q \mid \neg Q$.
  - Basic concepts $B ::= A \mid \exists Q$ for $A \in N_C, Q \in N_R$
  - Concepts $C ::= B \mid \neg B \mid \exists R.C$

  - TBox: $B \sqsubseteq C$, $(\mathit{func}\ Q)$ ("Q is functional") where Q does not appear as $\exists Q.C$ on rhs in TBox
  - ABox: $A(a), P(a,b)$
- Semantics as usual
  ($\exists Q$ shorthand for $\exists Q.\top$)

- Note
  - No qualified existential on lhs
  - Restriction on function role
  - Both due to rewritability

Properties

- DL-Lite$_{\mathcal{F}}$ enables basic UML conceptual modeling
  - ISA between classes ($\mathit{Professor} \sqsubseteq \mathit{Person}$)
  - Disjointness ($\mathit{Professor} \sqsubseteq \neg \mathit{Student}$)
  - Domain and range of roles: ($\mathit{Professor} \sqsubseteq \exists \mathit{teachesTo}$, $\exists \mathit{hasTutor}^- \sqsubseteq \mathit{Professor}$)
  - ...
- DL-Lite$_{\mathcal{F}}$ does not have finite model property

Example

- $\mathit{Nat} \sqsubseteq \exists \mathit{hasSucc}$, $\exists \mathit{hasSucc}^- \sqsubseteq \mathit{Nat}$, $(\mathit{funct}\ \mathit{hasSucc}^-)$,
- $\mathit{Zero} \sqsubseteq \mathit{Nat}$, $\mathit{Zero} \sqsubseteq \neg \exists \mathit{hasSucc}^-$, $\mathit{Zero}(0)$

DL-Lite$_\mathcal{R}$

- Another simple member of the family; allows role hierarchies

- Syntax
  - Basic role $Q ::= P \mid P^- $ for $P \in N_R$
  - Roles $R ::= Q \mid \neg Q$.
  - Basic concepts $B ::= A \mid \exists Q$ for $A \in N_C, Q \in N_R$
  - Concepts $C ::= B \mid \neg B \mid \exists R.C$

  - TBox: $B \sqsubseteq C$, $R_1 \sqsubseteq R_2$
  - ABox: $A(a), P(a, b)$
- Semantics as usual

- Note
  - Again no qualified existential on lhs
  - DL-Lite$_\mathcal{R}$ has finite model property

Qualified Existentials

- Qualified existentials on rhs not necessary (if role inclusions and inverse allowed)
- Can be eliminated conserving satisfiably equivalence

Example

- Input: $Student \sqsubseteq \exists hasTutor.Professor$
- Output
  - $hasProfTutor \sqsubseteq hasTutor$
  - $Student \sqsubseteq \exists hasProfTutor$
  - $\exists hasProfTutor^{-} \sqsubseteq Prof$

- In the following: We assume w.l.o.g. that only non-qualified existentials are used

DL-Lite$_{\mathcal{A}}$

- DL-Lite$_{\mathcal{A}}$ extends DL-Lite$_{\mathcal{F}}$ and DL-Lite$_{\mathcal{A}}$ by allowing for
  - attribute expressions (relation between objects and values)
  - identification assertions (corresponds to primary key constraints in DB)
- Restrictions for TBox: Roles (and attributes) appearing in functionality declarations or identification assertions must not appear on the rhs of role inclusions

Example (Football league example in DL-Lite$_\mathcal{A}$)

- $League \sqsubseteq \exists of$ (“Every league is the league . . .
- $\exists of^- \sqsubseteq Nation$ . . of some nation”)

- $League \sqsubseteq \delta(hasYear)$ (“Every league has a year”)
  (Here: $\delta(hasYear)$ = domain of attribute $hasYear$)
- $\rho(hasYear) \sqsubseteq xsd : positiveInteger$
  (“Range of hasYear are RDF literals of type positive integer”)

- (funct hasYear)

- $(id\ League\ of, hasYear)$
  (“Leagues are uniquely determined by the nation and the year”)

Rewritability of Query Answering

- UCQ over DL-Lite$_{\mathcal{A}}$ can be rewritten into FOL queries

Theorem

UCQs over DL-Lite$_{\mathcal{A}}$ are FOL-rewritable.

- We consider first the case where the ontology is satisfiable
- In this case rewriting is possible even into UCQs
- One can show that only positive inclusions (PIs) and not negative inclusions (NIs) are relevant
- PI: $A_1 \sqsubseteq A_2$, $\exists Q \sqsubseteq A_2$, $A_1 \sqsubseteq \exists Q_2$, $\exists Q_1 \sqsubseteq \exists Q_2$, $Q_1 \sqsubseteq Q_2$
- NI: $A_1 \sqsubseteq \neg A_2$, $\exists Q_1 \sqsubseteq \neg A_2$, $A_1 \sqsubseteq \neg \exists Q_2$, $\exists Q_1 \sqsubseteq \neg \exists Q_2$, $Q_1 \sqsubseteq \neg Q_2$

Example (Query answering by rewriting)

- $AssistantProf \sqsubseteq Prof$
- $\exists teaches^{-} \sqsubseteq Course$
- $Prof \sqsubseteq \exists teaches$

- $Prof(schroedinger)$
- $teaches(schroedinger, csCats)$
- $Course(csCats)$
- $Prof(einstein)$

$Q(x) = \exists y.teaches(x, y) \land Course(y)$

- QA by stepwise extension of the initial query
- Capture entailments of PIs in order to find also binding $x = einstein$
- Read PIs as rules applied from right to left

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- $Q_{rew}(x) \leftarrow teaches(x, y), Course(y)$
- $Q_{rew}(x) \leftarrow teaches(x, y), teaches(\_, y)$
- $Q_{rew}(x) \leftarrow teaches(x, y)$ (after unification/reduction)
- $Q_{rew}(x) \leftarrow teaches(x, \_)$ (after anonymization)
- $Q_{rew}(x) \leftarrow Prof(x)$
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- Resulting query Q_{rew} is an UCQ and is called the **perfect rewriting** of Q
- $ans(Q_{rew}, (\mathcal{A})) = \{schroedinger, einstein\} = cert(Q, (\mathcal{T}, \mathcal{A}))$

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- $\mathit{ans}(Q_{rew}, (\mathcal{A})) = \{\mathit{schroedinger}, \mathit{einstein}\} = \mathit{cert}(Q, (\mathcal{T}, \mathcal{A}))$

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Perfect Rewriting Algorithm PerfectRew(Q, TP)

```
Input  : Q = UCQ (in set notation), TP = DL-Lite_A PIs
Output: union of conjunctive queries PR
repeat
    PR' := PR;
    forall the q ∈ PR' do
        forall the g ∈ q do
            forall the PI I ∈ TP do
                if I is applicable to g then
                    PR := PR ∪ {ApplyPI(q, g, I)}
                end
            end
        end
        forall the g1, g2 in q do
            if g1 and g2 unify then
                PR := PR ∪ {anon(reduce(q, g1, g2))};
            end
        end
    end
until PR' = PR;
return PR;
```

- Anonymization: Substitute variables that are not bound with _.
- Variable is bound iff it is a distinguished variable or occurs at least twice in the body of a CQ

Properties of PerfectRew

- **Termination**
  - There are only finitely many different rewritings
- **Correctness**
  - Only certain answers are produced by the rewriting
  - Formally: $ans(Q_{rew}, \mathcal{A}) \subseteq cert(Q, (\mathcal{T}, \mathcal{A}))$
  - Clear, as PI applied correctly
- **Completeness**
  - All certain answers are produced by the rewriting
  - $ans(Q_{rew}, \mathcal{A}) \supseteq cert(Q, (\mathcal{T}, \mathcal{A}))$
  - How to prove this?
    $\Longrightarrow$ Our old friend, the **chase**, helps again

Chase Construction for DL

- The PIs of the TBox are read as (TGD) rules in the natural direction from left to right

- Resulting structure, the chase, also called **canonical model** here is **universal**
- Reminder: A universal model can be mapped homomorphically into any other model.

Theorem

Every satisfiable DL-Lite ontology has a canonical model

- Different from the approach in Date Exchange, one does not aim for finite chases (cannot be guaranteed)
- Chase used as tool for proving, e.g., completeness: Answering the rewritten query Q_{rew} on the ABox is the same as answering Q on the chase.

Satisfiability Check for Ontologies

- In case an ontology is unsatisfiable, answer set becomes trivial
  An unsatisfiable ontology entails all assertions
- Hence to determine correct answers, a satisfiability check is needed
- We will consider this in the following and show

Theorem

Checking (un-)satisfiability of DL-Lite ontologies is FOL rewritable.

That means: For any TBox there is a Boolean query Q such that for all ABoxes $\mathcal{A}$: $(\mathcal{T}, \mathcal{A})$ is satisfiable iff Q is false.

- Unsatisfiability may be caused by an NI (negative inclusion) or by a functional declaration
- So the rewritten query asks for an object in the ABox violating an NI or a functional declaration

FOL Rewritability of Satisfiability

Example

TBox	*ABox*
$Prof \sqsubseteq \neg Student$	$Student(alice)$
$\exists mentors \sqsubseteq Prof$	$mentors(alice, bob)$
$(funct\ mentors^{-})$	$mentors(andreia, bob)$

The ontology is made unsatisfiable by two culprits in the ABox:

- alice (via NI)

$$Q_1() \leftarrow \exists x.(Prof(x) \land Student(x)) \lor \exists x, y mentors(x, y) \land Prof(x)$$

- bob for the functional axiom

$$Q_2() \leftarrow \exists x, y, z.mentors(x, y) \land mentors(x, z) \land y \neq z$$

- Unsatisfiability tester query: $Q_1 \lor Q_2$

FOL Rewritability of Satisfiability

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FOL Rewritability of Satisfiability

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- Unsatisfiability tester query: $Q_1 \vee Q_2$

Checking Inconsistency for NIs

- Every NI is separately transformed to a CQ asking for a counterexample object, e.g.,

$A \sqsubseteq \neg B$	becomes	$Q() \leftarrow \exists x.A \land B$
$\exists P \sqsubseteq \neg B$	becomes	$Q() \rightarrow \exists y,x.P(x,y) \land B(x)$

- Resulting CQs are rewritten separately with PerfecRew w.r.t. PIs in the TBox
  - Intuition closure: $A \sqsubseteq B$ and $B \sqsubseteq \neg C$ entails $A \sqsubseteq \neg C$
  - Intuition separability: No two NIs can interact.
- $Q_N :=$ union of these CQs

- For functionalities, it is enough to consider these alone

$(funct\ P)$ becomes $Q() \leftarrow \exists x,y,z.P(x,y) \land P(x,z) \land y \neq z$

- $Q_F :=$ union of these CQs
  - Intuition: No interaction of PI or NI with functionalities

Rewritability

Theorem

Let $\mathcal{O} = (\mathcal{T}, \mathcal{A})$ be a DL-Lite$_{\mathcal{A}}$ ontology. Then:

$\mathcal{O}$ is satisfiable iff $Q_N \vee Q_F$ (which is a UCQ$^{\neq}$ and hence FOL query) is false.

- The separability has consequences for identifying culprits of inconsistency
  - At most two ABox axioms may be responsible for an inconsistency
  - This is relevant for ontology repair, version, change etc. (see next lectures)

Constructs Leading to Non-rewritability in DL-Lite

- DL-Lite$_{\mathcal{A}}$ is a maximal DL w.r.t. the allowed logical constructors under the FOL constraints
- Useful constructions such as qualified existentials, disjunction, non-restricted use of functional roles lead to non FOL-rewritability
- This can be proved using complexity theory and FOL (un-)definability arguments

Qualified existentials on Lhs

- Reachability in directed gaphs is known to be NLOGSPACE-complete
- Use the fact that

$$\text{FOL expressible } = AC^0 \subsetneq NLOGSPACE$$

and the following reachability-to-QA reduction

Reduction

$$\begin{array}{rcl} \text{Given:} & & \mathfrak{G}, \text{start } s, \text{ end } t \\ \mathcal{A}_{\mathfrak{G},t} & = & \{edge(v_1, v_2) \mid (v_1, v_2)\} \cup \{pathToTarget(t)\} \\ \mathcal{T} & = & \{\exists edge.PathToTarget \sqsubseteq PathToTarget\} \\ CQ & = & q() \leftarrow PathToTarget(s) \end{array}$$

- Fact: $\mathcal{T} \cup \mathcal{A}_{\mathfrak{G},t} \models q$ iff there is a path from s to t in $\mathfrak{G}$
- Fact: $\mathcal{T}, q$ do not depend on $\mathfrak{G}, t$
- Problem $\mathcal{T} \cup \mathcal{A}_{\mathfrak{G},t} \models q$ is NLOGSPACE hard

Limits of DL-Lite

- DL-Lite$_{\mathcal{A}}$ is not the maximal fragment of FOL allowing for rewritability

- Datalog$^{\pm}$ = Datalog with existentials in head = set of tuple generating (TGDs) rules (and EGDs)
  - Datalog$_0^{\pm}$ = "Linear fragment" of Datalog$^{\pm}$ containing rules whose body consists of one atom
  - Fact: Datalog$_0^{\pm}$ is strictly more expressive than DL-Lite.

Example

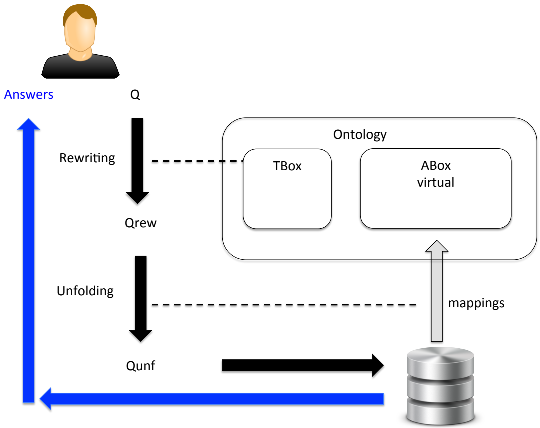
The rule

$$\forall x.\mathit{manager}(x) \rightarrow \mathit{manages}(x, x)$$

is in Datalog$_0^{\pm}$ but in no member of the DL-Lite family.

Unfolding

Connecting to the Real World: Mappings and Unfolding



Reminder: Mappings

- Mappings have an important role for OBDA

Schema of Mappings $\mathcal{M}$

m_1:	ontology template$_1$	$\longleftarrow$	data source template$_1$
m_2:	ontology template$_2$	$\longleftarrow$	data source template$_2$
	...		

- Lift data to the ontology level
  - Data level: (nearly) closed world
  - Ontology level: open world

- Mappings, described as **rules**, provide **declarative means** of implementing the lifting
  - User friendliness: users may built mappings on their own
  - Neat semantics: the semantics can be clearly specified and is not hidden in algorithms (as in direct mappings)
  - Modularity: mappings can be easly extended, combined etc.
  - Reuse of tools: Can be managed by (adapted) rule engines

The Burden of Mappings

- The data-to-ontology lift faces **impedance mismatch**
  - data values in the data vs.
  - abstract objects in the ontology world
  - Solved by Skolem terms $\vec{f}(\vec{x})$ below

Schema of Mappings

$$m : \psi(\vec{f}(\vec{x})) \longleftarrow Q(\vec{x}, \vec{y})$$

- $\psi(\vec{f}(\vec{x}))$: Query for generating ABox axioms
- $Q(\vec{x}, \vec{y})$: Query over the backend sources
- Function $\vec{f}$ translates backend instantiations of $\vec{x}$ to constants

- Mappings M over backend sources generates ABox $\mathcal{A}(M, DB)$.
- Use of mappings
  - as ETL (extract, transform, load) means: materialize ABox
  - as logical view means: ABox kept virtual (classical OBDA)

Example Scenario: Measurements

- Example schema for measurement and event data in DB

```
SENSOR(SID, CID, Sname, TID, description)
SENSORTYPE(TID, Tname)
COMPONENT(CID, superCID, AID, Cname)
ASSEMBLY(AID, AName, ALocation)
MEASUREMENT(MID, MtimeStamp, SID, Mval)
MESSAGE(MesID, MesTimeStamp, MesAssemblyID,  catID, MesEventText)
CATEGORY(catID, catName)
```

- For mapping

  m: $Sens(f(SID)) \land name(f(SID), y) \longleftarrow$

  ```
  SELECT SID,  Sname as y FROM SENSOR
  ```

- the row data in SENSOR table

SENSOR
(123, comp45, TC255, TempSens, 'A temperature sensor')

- generates facts

$Sens(f(123)), name(f(123), TempSens) \in \mathcal{A}(m, DB)$

Example Scenario: Measurements

- Example schema for measurement and event data in DB

```
SENSOR(SID, CID, Sname, TID, description)
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MEASUREMENT(MID, MtimeStamp, SID, Mval)
MESSAGE(MesID, MesTimeStamp, MesAssemblyID,  catID, MesEventText)
CATEGORY(catID, catName)
```

- For mapping

m: $\mathit{Sens}(f(\mathit{SID})) \wedge \mathit{name}(f(\mathit{SID}), y) \longleftarrow$

```
SELECT SID,  Sname as y FROM SENSOR
```

- the row data in SENSOR table

SENSOR
(123, comp45, TC255, TempSens, ‘A temperature sensor’)

- generates facts

$\mathit{Sens}(f(123)), \mathit{name}(f(123), \mathit{TempSens}) \in \mathcal{A}(m, DB)$

R2RML

- Very expressive mapping language couched in the RDF terminology
- Read only (not to allowed to write the RDFs view generated by the mappings)
- W3C standard (since 2012), `http://www.w3.org/TR/r2rml/`
- Defined for logical tables (= SQL table or SQL view or R2RML view)
  $\Longrightarrow$ they can be composed to chains of mappings
- Has means to model foreign keys (referencing object map)

Example (R2RML for Sensor Scenario)

```
@prefix rdf : <http ://www.w3.org/1999/02/22?rdf?syntax?ns#> .
@prefix rr : <http ://www.w3. org/ns/r2rml#> .
@prefix ex : <http ://www. example . org/> .

ex : SensorMap
    a rr:TriplesMap ;
    rr: logicalTable [ rr : tableName ‘‘Senso’’ ] ;
    rr : subjectMap [
        rr:template ‘‘http://www.sensorworld.org/SID’’ ;
        rr:class ex:Sensor
    ];
    rr: predicateObjectMap [
        rr:predicate ex:hasName;
        rr:objectMap [column ‘‘name’’]
    ] .
```

OBDA semantics with Mappings

- Semantics canonically specified by using the generated ABox $\mathcal{A}(DB, \mathcal{M})$
- **Ontology Based Data Access System (OBDAS)**

$$\mathcal{OS} = (\underbrace{\mathcal{T}}_{\textit{TBox}}, \overbrace{\mathcal{M}}^{\text{mappings}}, \underbrace{DB}_{\text{relational data base}})$$

Definition

An interpretation $\mathcal{I}$ **satisfies an OBDAS** $\mathcal{OS} = (\mathcal{T}, \mathcal{M}, DB)$, for short: $\mathcal{I} \models \mathcal{OS}$, iff $\mathcal{I} \models (\mathcal{T}, \mathcal{A}(DB, \mathcal{M}))$

An OBDAS is satisfiable iff it has a satisfying interpretation.

Unfolding

- Unfolding is the second but not to be underestimated step in classical OBDA QA
- Applies mappings in the inverse direction to produce query Q_{unf} over data sources which then becomes evaluated

Unfolding steps

1. **Split** mappings
   $atom_1 \wedge \cdots \wedge atom_n \longleftarrow Q$ becomes
   $atom_1 \longleftarrow Q, \ldots, atom_n \longleftarrow Q$
2. Introduce **auxiliary predicates** (views for SQL) for rhs queries
3. In Q_{rew} **unfold** the atoms (with unification) into a UCQ Q_{aux} using purely auxiliary predicates
4. **Translate Q_{aux} into SQL**
   - logical conjunction of atoms realized by a join
   - disjunction of queries realized by SQL UNION

Example

Unfolding for Measurement Scenario

- DB with schema

```
SENSOR(SID, CID, Sname, TID, description)
MEASUREMENT1(MID, MtimeStamp, SID, Mval)
MEASUREMENT2(MID, MtimeStamp, SID, Mval) ...
```

- Mappings

m1: $Sens(f(SID)) \wedge name(f(SID), y) \longleftarrow$

```
SELECT SID, Sname as y FROM SENSOR
```

m2: $hasVal(f(SID), Mval) \longleftarrow$

```
SELECT SID, Mval FROM Measurement1
```

m3: $hasVal(f(SID), Mval) \longleftarrow$

```
SELECT SID, Mval FROM Measurement2
```

m4: $criticalValue(Mval) \longleftarrow$

```
SELECT Mval FROM MEASUREMENT1
WHERE Mval > 300
```

- Query

$Q(x) \longleftarrow Sens(x) \wedge hasVal(x, y) \wedge Critical(y)$

Example

Unfolding for Measurement Scenario

- Split mappings

m1.1: $Sens(f(SID)) \longleftarrow$
```
SELECT SID FROM SENSOR
```
m1.2: $name(f(SID), y) \longleftarrow$
```
SELECT SID, Sname as y FROM SENSOR
```
m2: $hasVal(f(SID), Mval) \longleftarrow$
```
SELECT SID, Mval FROM Measurement1
```
m3: $hasVal(f(SID), Mval) \longleftarrow$
```
SELECT SID, Mval FROM Measurement2
```
m4: $criticalValue(Mval) \longleftarrow$
```
SELECT Mval FROM MEASUREMENT1
WHERE Mval > 300
```

- Query

$$Q(x) \quad \longleftarrow \quad Sens(x) \wedge hasVal(x, y) \wedge Critical(y)$$

Example

Unfolding for Measurement Scenario

- Split mappings

m1.1: $Sens(f(SID)) \longleftarrow$

`SELECT SID FROM SENSOR` =:Aux1(SID)

m1.2: $name(f(SID), y) \longleftarrow$

`SELECT SID, Sname as y FROM SENSOR` =:Aux2(SID,y)

m2: $hasVal(f(SID), Mval) \longleftarrow$

`SELECT SID, Mval FROM Measurement1` =:Aux3(SID,Mval)

m3: $hasVal(f(SID), Mval) \longleftarrow$

`SELECT SID, Mval FROM Measurement2` =:Aux4(SID,Mval)

m4: $criticalValue(Mval) \longleftarrow$

```
SELECT Mval FROM MEASUREMENT1
WHERE Mval > 300
```
=:Aux5(Mval)

- Query

$$Q(x) \quad \longleftarrow \quad Sens(x) \wedge hasVal(x, y) \wedge Critical(y)$$

Example

Unfolding for Measurement Scenario

- Split mappings

m1.1: $Sens(f(SID)) \longleftarrow$

`SELECT SID FROM SENSOR` :=Aux(SID)

m1.2 : $name(f(SID), y) \longleftarrow$

`SELECT SID, Sname as y FROM SENSOR` =:Aux2(SID,y)

m2: $hasVal(f(SID), Mval) \longleftarrow$

`SELECT SID, Mval FROM Measurement1` =:Aux3(SID,Mval)

m3: $hasVal(f(SID), Mval) \longleftarrow$

`SELECT SID, Mval FROM Measurement2` =:Aux4(SID,Mval)

m4: $criticalValue(Mval) \longleftarrow$

```
SELECT Mval FROM MEASUREMENT1
WHERE Mval > 300
```

=:Aux5(Mval)

- Query

$$Q(x) \quad \longleftarrow \quad Sens(x) \wedge hasVal(x, y) \wedge Critical(y)$$

- Query Q_{Aux} with Aux-views

$$Q_{Aux} \quad \longleftarrow \quad Aux1(SID), Aux3(SID, Mval), Aux5(Mval)$$
$$Q_{Aux} \quad \longleftarrow \quad Aux1(SID), Aux4(SID, Mval), Aux5(Mval)$$

Example

Unfolding for Measurement Scenario

```
SELECT 'Qunfold' || aux_1.SID || ')' FROM
    (SELECT  SID FROM SENSOR) as aux_1,
    ( SELECT  SID,  Mval  FROM Measurement1) as aux_3,
    (SELECT  Mval   FROM MEASUREMENT1 WHERE Mval > 300) as aux_5
    WHERE aux_1.SID = aux_3.SID AND aux_3.Mval = aux_5.Mval
UNION
SELECT 'Qunfold' || aux_1.SID || ')' FROM
    (SELECT  SID FROM SENSOR) as aux_1,
    ( SELECT  SID,  Mval  FROM Measurement2) as aux_4,
    (SELECT  Mval   FROM MEASUREMENT1 WHERE Mval > 300) as aux_5
    WHERE aux_1.SID = aux_4.SID AND aux_4.Mval = aux_5.Mval
```

- There are different forms of unfolding

Research on OBDA Mappings

- Recent research on classical OBDA reflects the insight of mappings' importance

- Adequateness conditions for mappings
  - consistency/coherency
  - redundancy

- Management of mappings
  - Repairing mappings (based on consistency notion)
  - Approximating ontologies and mappings

Lit: D. Lembo et al. Mapping analysis in ontology-based data access: Algorithms and complexity. In: ISWC 2015, volume 9366 of LNCS, pages 217–234, 2015.

Need for Opimizations

- UCQ-Rewritings may be exponentially larger than the original query
- Have to deal with this problem in practical systems
- Use different rewriting to ensure **conciseness**
- Use additional knowledge on the data: integrity constraints, (H)-completeness

- Have a look at OBDA framework ontop (`http://ontop.inf.unibz.it/`)
  - Open source
  - available as Protege plugin
  - implementing many optimizations

Exercise 6

Exercise 6.1 (2 Points)

Prove that DL-Lite$_{\mathcal{F}}$ can have ontologies having only infinite models (using, e.g., the example mentioned in the lecture)

Exercise 6.2 (3 Points)

The anonymization function in the PerfRew algorithm is allowed to be applied only to un-bound variables that are not distinguished (that is are not answer variables). Give an example why this restriction makes sense.

Exercise 6.3 (3 Points)

Explain the notion of reification, and show (with an example) why it is needed for (classical) OBDA.

Exercise 6.4 (4 Points)

Many relevant DL reasoning services can be reduced to ontology satisfiability in DL-Lite. Show that subsumption w.r.t. a DL-Lite TBox can be reduced to (un)satisfiability test of a DL-Lite ontology!

Hint: Use the general fact of entailment that $\psi \models \phi$ iff $\psi \wedge \neg\phi$ is unsatisfiable. Then think of how the latter can be formulated in a DL-Lite ontology (introducing perhaps new symbols).