# Optimizing Ontology-Based Data Access

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# Use case: Statoil Exploration

*Experts in geology and geophysics develop stratigraphic models of unexplored areas on the basis of data acquired from previous operations at nearby geographical locations.*


Facts:

- 1,000 TB of relational data
- using diverse schemata
- spread over 2,000 tables, over multiple individual data bases

Data Access for Exploration:

- 900 experts in Statoil Exploration.
- up to 4 days for new data access queries, requiring assistance from IT-experts.
- 30–70% of time spent on data gathering.

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# Example 2: Siemens Energy Services

*Runs service centers for power plants, each responsible for remote monitoring and diagnostics of many thousands of gas/steam turbines and associated components. When informed about potential problems, diagnosis engineers access a variety of raw and processed data.*


Facts:

- several TB of time-stamped sensor data
- several GB of event data ("alarm triggered at time T")
- data grows at 30GB per day (sensor data rate 1Hz–1kHz)

Service Requests:

- over 50 service centers worldwide
- 1,000 service requests per center per year
- 80% of time per request used on data gathering

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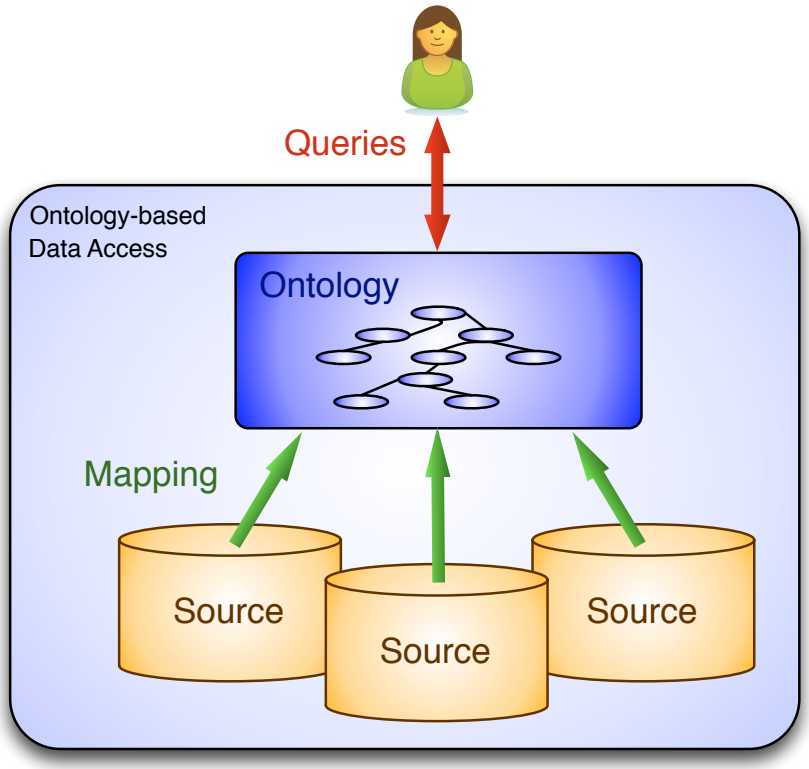
# Proposed solution: Ontology-based Data Access

Manage data adopting principles and techniques studied in **Knowledge Representation** in Artificial Intelligence.

- Based on formalisms grounded in logic, with well understood semantics and computational properties.
- Provide a conceptual, high level representation of the domain of interest in terms of an **ontology**.
- Do **not migrate the data** but leave it in the sources.
- **Map** the ontology to the data sources.
- Specify all information requests to the data in terms of the ontology.
- Use the inference services of the OBDA system to translate the requests into queries to the data sources.

# Ontology-based data access: Architecture




Based on three main components:

- Ontology: provides a unified, conceptual view of the managed information.
- Data source(s): are external and independent (possibly multiple and heterogeneous).
- Mappings: semantically link data at the sources with the ontology.

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# Ontology-based data access: Formalization

An **ontology-based access system** is a triple $\mathcal{O} = \langle \mathcal{T}, \mathcal{S}, \mathcal{M} \rangle$, 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 (federated) relational database representing the sources;
- $\mathcal{M}$ is a set of mapping assertions, each one of the form

$$\Phi(\vec{x}) \rightsquigarrow \Psi(\vec{x})$$

  where
  - $\Phi(\vec{x})$ is a FOL query over $\mathcal{S}$, returning tuples of values for $\vec{x}$
  - $\Psi(\vec{x})$ is a FOL query over $\mathcal{T}$ whose free variables are from $\vec{x}$.

# Ontology-based data access: Semantics

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

## Def.: **Semantics of an OBDA system**

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

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

## Def.: **Semantics of mappings**

We say that $\mathcal{I}$ **satisfies** $\Phi(\vec{x}) \rightsquigarrow \Psi(\vec{x})$ w.r.t. a database $\mathcal{S}$, if the FOL sentence

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

is true in $\mathcal{I} \cup \mathcal{S}$.

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# Instantiating the framework

1. Which is the "right" **query language**?
2. Which is the "right" **ontology language**?
3. Which is the "right" **mapping language**?

The choices that we make have to take into account the tradeoff between expressive power and efficiency of inference/query answering.

We are in a setting where we want to access large amounts of data, so **efficiency w.r.t. the data** plays an important role.

# Outline

# Use of mappings

In an OBDA system $\mathcal{O} = \langle \mathcal{T}, \mathcal{M}, \mathcal{S} \rangle$, the mapping $\mathcal{M}$ encodes how the data in $\mathcal{S}$ should be used to populate $\mathcal{O}$.

*Observe:*

- The data sources $\mathcal{S}$ and the mapping $\mathcal{M}$ define a virtual ABox $\mathcal{V} = \mathcal{M}(\mathcal{S})$, and queries are answered wrt $\mathcal{T}$ and $\mathcal{V}$.
- We do not really materialize the data of $\mathcal{V}$ (that's why it is called virtual).
- Instead, the intensional information in $\mathcal{T}$ and $\mathcal{M}$ is used to translate (i.e., rewrite and unfold) queries over $\mathcal{T}$ into queries formulated over $\mathcal{S}$.

# The impedance mismatch problem

We have an **impedance mismatch** problem

- In relational databases, information is represented as tuples of values.
- In ontologies, information is represented using both objects and values ...
  - ... with objects playing the main role, ...
  - ... and values a subsidiary role as fillers of object's attributes.

Proposed solution:

- We use **constructors to create objects** of the ontology from tuples of values in the DB.
- The constructors are modeled through Skolem functions in the query over the ontology part of the mapping:

$$\Phi(\vec{x}) \rightsquigarrow \Psi(\vec{\mathbf{f}}, \vec{x})$$

- Techniques from partial evaluation of logic programs are adapted for the unfolding of queries over $\mathcal{T}$ into queries over $\mathcal{S}$ using $\mathcal{M}$.

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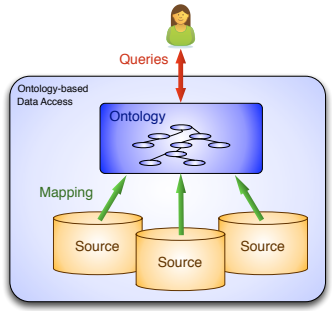
# Outline

# Incomplete information

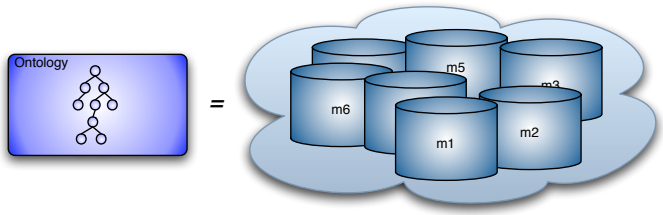



We are in a setting of **incomplete information**!!!

Incompleteness introduced:

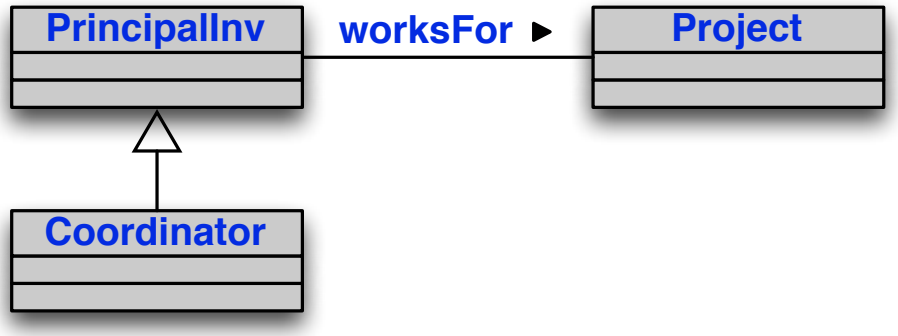
- by data source(s), in general assumed to be incomplete;
- by domain constraints encoded in the ontology.

**Plus:** Ontologies are logical theories, and hence perfectly suited to deal with incomplete information!




**Minus:** Query answering amounts to **logical inference**, and hence is significantly more challenging.

# Incomplete information – Example




Assume for simplicity that each table in the underlying database is mapped directly to (at most) one ontology concept/relationship.

But the database tables may be **incompletely specified**, or even missing for some concepts/relationships.

DB: Coordinator $\supseteq$ { arild, franz }
Project $\supseteq$ { optique, seals }
worksFor $\supseteq$ { (arild,optique), (ian,seals) }

Query: $q(x) \leftarrow \text{PrincipalInv}(x)$

Answer: { arild, franz, ian }

# Query answering

## Certain answers

Query answering amounts to finding the **certain answers** $cert(q, \mathcal{O})$ to a query $q(\vec{x})$, i.e., those answers that hold in all models of the OBDA system $\mathcal{O}$.

Two borderline cases for the language to use for querying ontologies:

1. Use the ontology language as query language.
   - Ontology languages are tailored for capturing intensional relationships.
   - They are quite **poor as query languages**.
2. Full SQL (or equivalently, first-order logic).
   - Problem: in the presence of incomplete information, query answering becomes **undecidable** (FOL validity).

A good tradeoff is to use **conjunctive queries** (CQs) or unions of CQs (UCQs), corresponding to SQL/relational algebra **(union) select-project-join queries**.

# Complexity of conjunctive query answering in DLs

Studied extensively for various ontology languages:

| | Combined complexity | Data complexity |
|---|---|---|
| Plain databases | NP-complete | in $AC^0$ (1) |
| Expressive DLs | $\geq$ 2ExpTime (2) | coNP-hard (3) |

(1) This is what we need to scale with the data.

(2) Hardness by [Lutz, 2008; Eiter *et al.*, 2009].
Tight upper bounds obtained for a variety of expressive DLs [Calvanese *et al.*, 1998; Levy and Rousset, 1998; Calvanese *et al.*, 2007c; Calvanese *et al.*, 2008c; Glimm *et al.*, 2008b; Glimm *et al.*, 2008a; Lutz, 2008; Eiter *et al.*, 2008].

(3) Already for an ontology with a single axiom involving disjunction.
However, the complexity does not increase even for very expressive DLs [Ortiz *et al.*, 2006; Ortiz *et al.*, 2008; Glimm *et al.*, 2008a].

# Challenges in OBDA

## Challenges

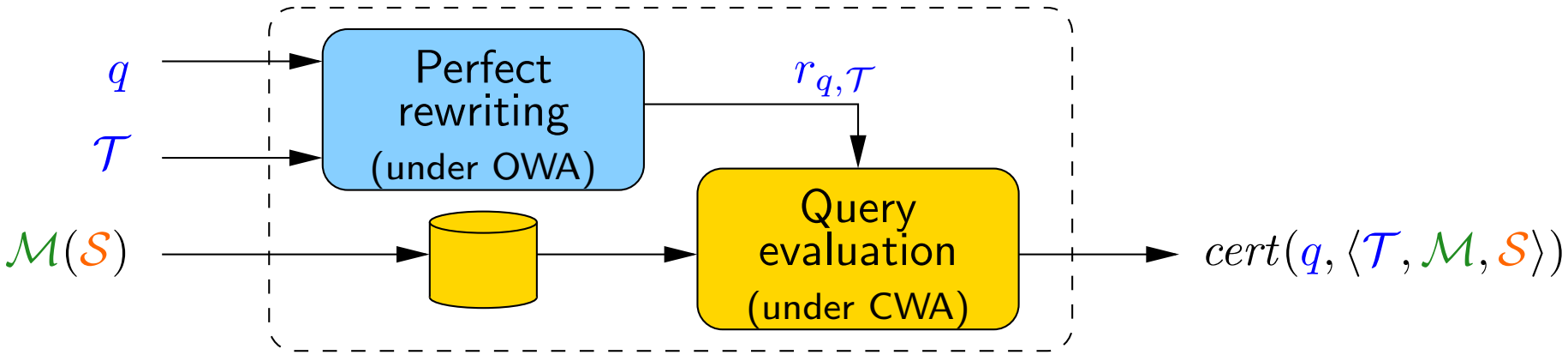
- Can we find interesting ontology languages for which query answering in OBDA can be done efficiently (i.e., in $AC^0$)?
- If yes, can we leverage relational database technology for query answering in OBDA?

# Logical inference for query answering


To be able to deal with data efficiently, we need to separate the contribution of the data $\mathcal{S}$ (accessed via the mapping $\mathcal{M}$) from the contribution of $q$ and $\mathcal{O}$.

$\rightsquigarrow$ Query answering by **query rewriting**.

# Query answering by rewriting




Query answering can always be thought as done in two phases:

1. **Perfect rewriting**: produce from $q$ and the ontology TBox $\mathcal{T}$ a new query $r_{q,\mathcal{T}}$ (called the perfect rewriting of $q$ w.r.t. $\mathcal{T}$).
2. **Query evaluation**: evaluate $r_{q,\mathcal{T}}$ over $\mathcal{M}(\mathcal{S})$ seen as a complete database (and without considering $\mathcal{T}$).
   $\rightsquigarrow$ Produces $cert(q, \langle \mathcal{T}, \mathcal{M}, \mathcal{S} \rangle)$.

We choose the ontology language in such a way that query answering is **FOL-rewritable**, i.e., the perfect rewriting $r_{q,\mathcal{T}}$ can be expressed in FOL (i.e., SQL), hence can be evaluated by a relational DBMS.

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# Outline

# The *DL-Lite* family

- A family of DLs optimized according to the tradeoff between expressive power and **complexity** of query answering, with emphasis on **data**.
  - The same complexity as relational databases.
  - In fact, **query answering is FOL-rewritable** and hence can be delegated to a relational DB engine.
  - The DLs of the *DL-Lite* family are essentially the maximally expressive DLs enjoying these nice computational properties.
- Nevertheless they have the "right" expressive power: capture the essential features of conceptual modeling formalisms.

**DL-Lite** provides robust foundations for Ontology-Based Data Access.

*Note:* The *DL-Lite* family is at the basis of the OWL 2 QL profile of the W3C standard Web Ontology Language OWL.

# *DL-Lite* ontologies (essential features)

Concept and role language:

- Roles $R$: either atomic: $P$
  or an inverse role: $P^-$
- Concepts $C$: either atomic: $A$
  or the projection of a role on one component: $\exists P$, $\exists P^-$

TBox assertions:

| | | | |
|---|---|---|---|
| Role inclusion: | $R_1 \sqsubseteq R_2$ | Concept inclusion: | $C_1 \sqsubseteq C_2$ |
| Role disjointness: | $R_1 \sqsubseteq \neg R_2$ | Concept disjointness: | $C_1 \sqsubseteq \neg C_2$ |
| Role functionality: | (**funct** $Q$) | | |

ABox assertions: $A(c)$, $P(c_1, c_2)$, with $c_1$, $c_2$ constants

*Note:* *DL-Lite* distinguishes also between abstract objects and data values (ignored here).

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# *DL-Lite* captures conceptual modeling formalisms

| Modeling construct | *DL-Lite* | FOL formalization |
|---|---|---|
| ISA on classes | $A_1 \sqsubseteq A_2$ | $\forall x(A_1(x) \rightarrow A_2(x))$ |
| Disjointness of classes | $A_1 \sqsubseteq \neg A_2$ | $\forall x(A_1(x) \rightarrow \neg A_2(x))$ |
| 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)* | $A_1 \sqsubseteq \exists P$<br>$A_2 \sqsubseteq \exists P^-$ | $\forall x(A_1(x) \rightarrow \exists y(P(x,y)))$<br>$\forall x(A_2(x) \rightarrow \exists y(P(y,x)))$ |
| Functionality *(max card = 1)* | (**funct** $P$)<br>(**funct** $P^-$) | $\forall x,y,y'(P(x,y) \wedge P(x,y') \rightarrow y = y')$<br>$\forall x,x',y(P(x,y) \wedge P(x',y) \rightarrow x = x')$ |
| ISA on relations | $R_1 \sqsubseteq R_2$ | $\forall x,y(R_1(x,y) \rightarrow R_2(x,y))$ |
| Disjointness of relations | $R_1 \sqsubseteq \neg R_2$ | $\forall x,y(R_1(x,y) \rightarrow \neg R_2(x,y))$ |
| ... | ... | ... |

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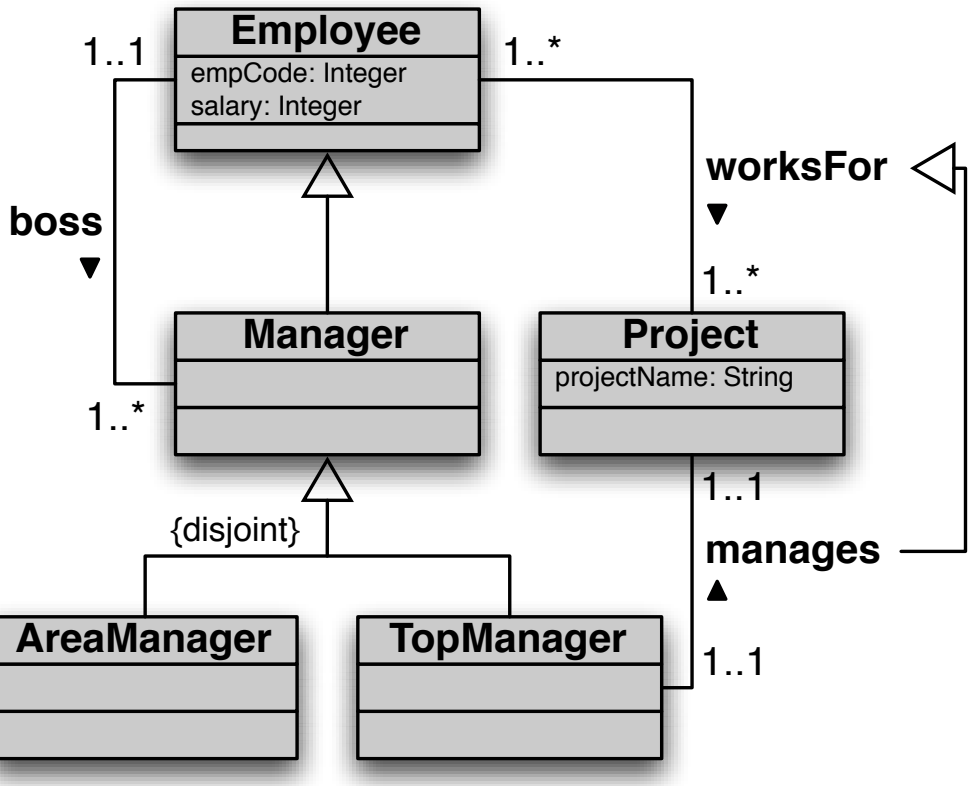
# Capturing UML class diagrams/ER schemas in *DL-Lite*




$$
\begin{aligned}
\text{Manager} &\sqsubseteq \text{Employee}\\
\text{AreaManager} &\sqsubseteq \text{Manager}\\
\text{TopManager} &\sqsubseteq \text{Manager}\\
\text{AreaManager} &\sqsubseteq \neg\text{TopManager}
\end{aligned}
$$

$$
\begin{aligned}
\text{Employee} &\sqsubseteq \exists \mathit{salary}\\
\exists \mathit{salary}^- &\sqsubseteq \texttt{xsd:int}\\
&(\textbf{funct}\ \mathit{salary})
\end{aligned}
$$

$$
\begin{aligned}
\exists\text{worksFor} &\sqsubseteq \text{Employee}\\
\exists\text{worksFor}^- &\sqsubseteq \text{Project}\\
\text{Employee} &\sqsubseteq \exists\text{worksFor}\\
\text{Project} &\sqsubseteq \exists\text{worksFor}^-
\end{aligned}
$$

$$
\begin{aligned}
\exists\text{manages} &\sqsubseteq \text{TopManager}\\
\exists\text{manages}^- &\sqsubseteq \text{Project}\\
\text{TopManager} &\sqsubseteq \exists\text{manages}\\
\text{Project} &\sqsubseteq \exists\text{manages}^-\\
\text{manages} &\sqsubseteq \text{worksFor}\\
&(\textbf{funct}\ \text{manages})\\
&(\textbf{funct}\ \text{manages}^-)\\
&\cdots
\end{aligned}
$$

*Note:* *DL-Lite* cannot capture completeness of a hierarchy. This would require **disjunction** (i.e., **OR**).

# Query answering in *DL-Lite*

Based on query rewriting: given a (U)CQ $q$ and an ontology $\mathcal{O} = \langle \mathcal{T}, \mathcal{A} \rangle$:

1. **Compute the perfect rewriting of $q$ w.r.t. $\mathcal{T}$**, which is a FOL query.
2. **Evaluate the perfect rewriting** over $\mathcal{A}$. (Ignore the mapping for now.)

To compute the perfect rewriting, starting from $q$, iteratively get a CQ to be processed and either:

- **expand an atom** using an inclusion axiom, or
- **unify** atoms in the CQ to obtain a more specific CQ to be further expanded.

Each result of the above steps is added to the queries to be processed.

We can restrict expansion and unification so as to ensure termination without losing completeness.

*Note:* negative inclusions and functionalities play a role in ontology satisfiability, but can be ignored during query answering (i.e., we have **separability**).

# Query answering in *DL-Lite* – Example

TBox:

$\mathsf{Coordinator} \sqsubseteq \mathsf{PrincipalInv}$ $\quad \forall x(\mathsf{Coordinator}(x) \rightarrow \mathsf{PrincipalInv}(x))$

$\mathsf{PrincipalInv} \sqsubseteq \exists \mathsf{worksFor}$ $\quad \forall x(\mathsf{PrincipalInv}(x) \rightarrow \exists y(\mathsf{worksFor}(x, y)))$

$\exists \mathsf{worksFor}^- \sqsubseteq \mathsf{Project}$ $\quad \forall x(\exists y(\mathsf{worksFor}(y, x)) \rightarrow \mathsf{Project}(x))$

Query: $\mathsf{q}(x) \leftarrow \mathsf{worksFor}(x, y), \mathsf{Project}(y)$

Perfect rewriting:

$\mathsf{q}(x) \leftarrow \mathsf{worksFor}(x, y), \mathsf{Project}(y)$

$\mathsf{q}(x) \leftarrow \mathsf{worksFor}(x, y), \mathsf{worksFor}(\_, y)$

$\mathsf{q}(x) \leftarrow \mathsf{worksFor}(x, \_)$

$\mathsf{q}(x) \leftarrow \mathsf{PrincipalInv}(x)$

$\mathsf{q}(x) \leftarrow \mathsf{Coordinator}(x)$

ABox: $\mathsf{worksFor}(\mathtt{arild}, \mathtt{optique})$ $\quad \mathsf{Coordinator}(\mathtt{arild})$

$\mathsf{worksFor}(\mathtt{ian}, \mathtt{seals})$ $\quad \mathsf{Coordinator}(\mathtt{franz})$

Evaluating the queries over the ABox (seen as a DB) produces as answer $\{\mathtt{arild}, \mathtt{ian}, \mathtt{franz}\}$.

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# Complexity of reasoning in *DL-Lite*

Ontology satisfiability and all classical DL reasoning tasks are:

- Efficiently tractable in the size of the TBox (i.e., PTIME).
- Very efficiently tractable in the size of the ABox (i.e., $AC^0$).

In fact, reasoning can be done by constructing suitable FOL/SQL queries and evaluating them over the ABox (FOL-rewritability).

Query answering for CQs and UCQs is:

- PTIME in the size of the TBox.
- $AC^0$ in the size of the ABox.
- Exponential in the size of the **query** (NP-complete).
  Bad? . . . not really, this is exactly as in relational DBs.

So, is everything solved and can we deploy this technology?
**NO! Efficiency is a major issue!**

# Outline

# Size of the rewriting

Even in the presence of a shallow hierarchy in the TBox, the perfect rewriting, when expressed as a UCQ, may be very large in the original query.

Consider the query: $q(x) \leftarrow A_1(x), A_2(x), \ldots, A_n(x)$

and the concept inclusions: $B_1 \sqsubseteq A_1 \quad \cdots \quad B_n \sqsubseteq A_n$.

In the UCQ perfect rewriting of $q$, we have all CQs of the form

$$q(x) \leftarrow Z_1(x), Z_2(x), \ldots, Z_n(x)$$

where each $Z_i$ stands for either $A_i$ or $B_i$.

**There are $2^n$ such CQs!**
Unfortunately, this blowup **occurs also in practice**.

# Optimizing OBDA

- Novel techniques ensure more compact rewritings [Kontchakov *et al.*, 2010; Rosati and Almatelli, 2010; Gottlob and Schwentick, 2012; Kikot *et al.*, 2012].
- However, what matters is the **efficiency of evaluation by the DBMS**, not the size of the rewriting.
- Optimizing rewriting is necessary but not sufficient, since the more compact rewritings are much more difficult to evaluate.

**Holistic approach** is required, that considers all components of an OBDA system, i.e.:

- the TBox $\mathcal{T}$,
- the mappings $\mathcal{M}$, and
- the data sources $\mathcal{S}$ with their constraints.

# Exploiting data constraints for optimization

- Ontology TBox pruning using constraints and mappings.
- Semantic index to efficiently deal with concept hierarchies.
- Rewriting optimization using constraints and mappings.

The constraints on the data induce via the mapping $\mathcal{M}$ between $\mathcal{T}$ and $\mathcal{S}$ **dependencies in the ABox**.

# ABox dependencies

ABox dependencies express **constraints on the data in the ABox**.

- Syntax: $C_1 \preceq C_2$ $R_1 \preceq R_2$
- Meaning: constrain the assertions present in the ABox
  - $\mathcal{A} \vdash A_1 \preceq A_2$ iff $A_1(d) \in \mathcal{A}$ implies $A_2(d) \in \mathcal{A}$
  - $\mathcal{A} \vdash A \preceq \exists P$ iff $A(d) \in \mathcal{A}$ implies $P(d, d') \in \mathcal{A}$ for some $d'$
  - $\mathcal{A} \vdash P_1 \preceq P_2$ iff $P_1(d, d') \in \mathcal{A}$ implies $P_2(d, d') \in \mathcal{A}$
  - $\cdots$

*Note:* ABox dependencies are fundamentally different from TBox assertions. They constrain the syntactic level (the ABox itself), and not the models.

# Avoiding redundant inferences

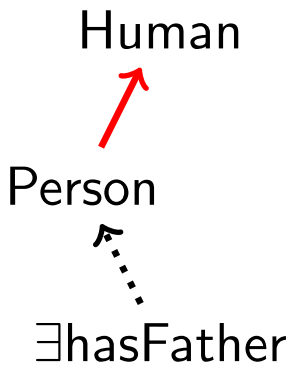
ABox dependencies can be exploited to avoid redundant inferences in query answering:

- Optimize the TBox by eliminating TBox assertions while maintaining completeness of query answering wrt ABoxes satisfying the dependencies.
- Optimize query rewriting algorithm so as to eliminate rewritings that are redundant wrt query containment under dependencies.

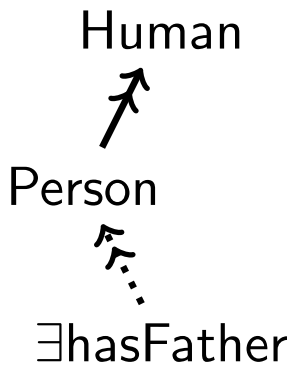
# Characterizing redundancy – Direct redundancy case 1

TBox optimization is based on a characterization of TBox assertions that are **redundant** wrt a set of ABox dependencies.

Let $\mathcal{T}$ be the hierarchy:




'$\rightarrow$' is redundant in $\mathcal{T}$ if $\Sigma$ is:

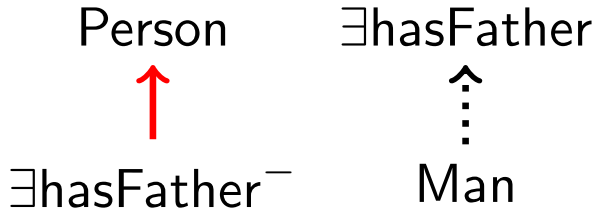



Note: $\Sigma$ may enforce e.g., that

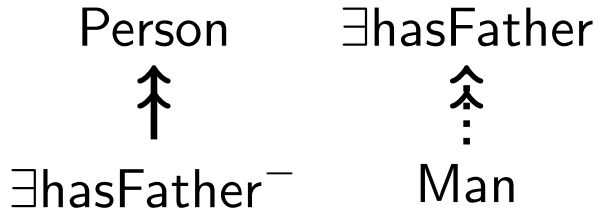
$$\text{hasFather}(\text{luisa}, \text{franz}) \in \mathcal{A} \quad \text{implies} \quad \text{Human}(\text{luisa}) \in \mathcal{A}.$$

# Characterizing redundancy – Direct redundancy case 2

Let $\mathcal{T}$ be the following TBox:




'$\rightarrow$' is redundant if $\Sigma$ is:




Note: $\Sigma$ may enforce e.g., that

$\text{Man}(\text{john}) \in \mathcal{A}$ implies there is some $d$ s.t. $\text{hasFather}(\text{john}, d) \in \mathcal{A}$ and $\text{Person}(d) \in \mathcal{A}$.

Note: '$\rightarrow$' would **not** be redundant if in $\Sigma$ we have:

$$\text{Man} \not\sqsubseteq \exists \text{hasFather}.$$

# TBox optimization

A TBox assertion might also be indirectly redundant (more complicated definition).

**Optimized query answering** wrt a TBox $\mathcal{T}$ and a set of ABox dependencies $\Sigma$:

1. Compute the deductive closure $\mathcal{T}_{cl}$ of $\mathcal{T}$ (at most quadratic in size of $\mathcal{T}$).
2. Compute the deductive closure $\Sigma_{cl}$ of $\Sigma$ (at most quadratic in size of $\Sigma$).
3. Eliminate from $\mathcal{T}_{cl}$ all TBox assertions that are redundant wrt $\Sigma_{cl}$, obtaining a TBox $\mathcal{T}_{opt}$.
4. Rewrite the query wrt $\mathcal{T}_{opt}$.
5. Evaluate the rewritten query over the ABox.

*Notes:*

- $\mathcal{T}_{opt}$ can be computed in polynomial time in the size of $\mathcal{T}$ and $\Sigma$.
- $\mathcal{T}_{opt}$ might be much smaller than $\mathcal{T}$.
- $\mathcal{T}_{opt}$ can be used instead of $\mathcal{T}$ independently of the adopted query rewriting method (provided the ABox satisfies $\Sigma$).

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