Semantic Technologies for Data Access and Integration

Part 3: Query Processing and Optimization

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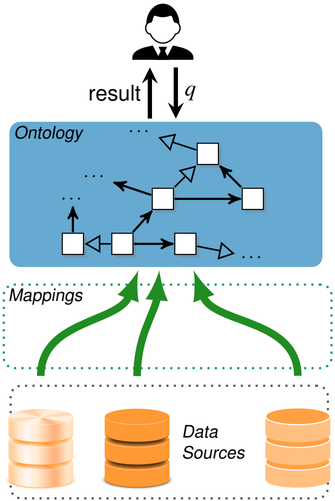
Query answering by query rewriting



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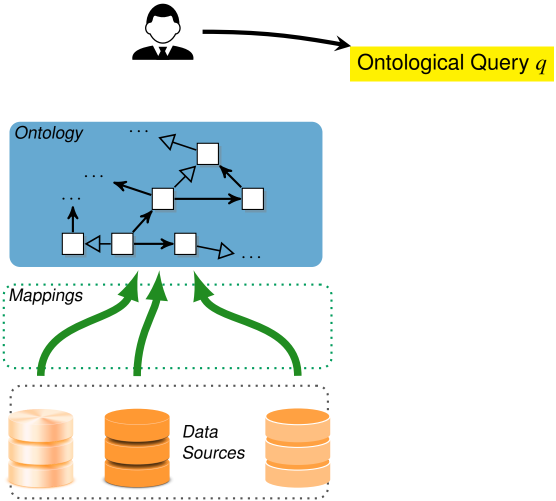

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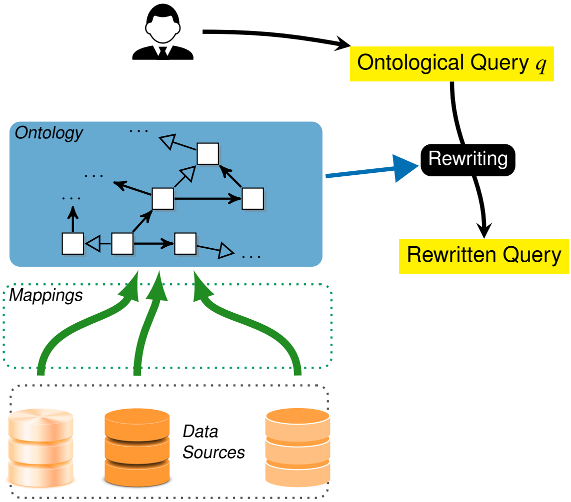

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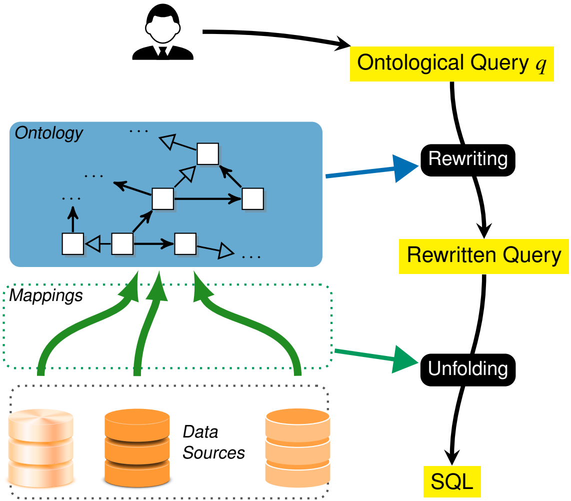

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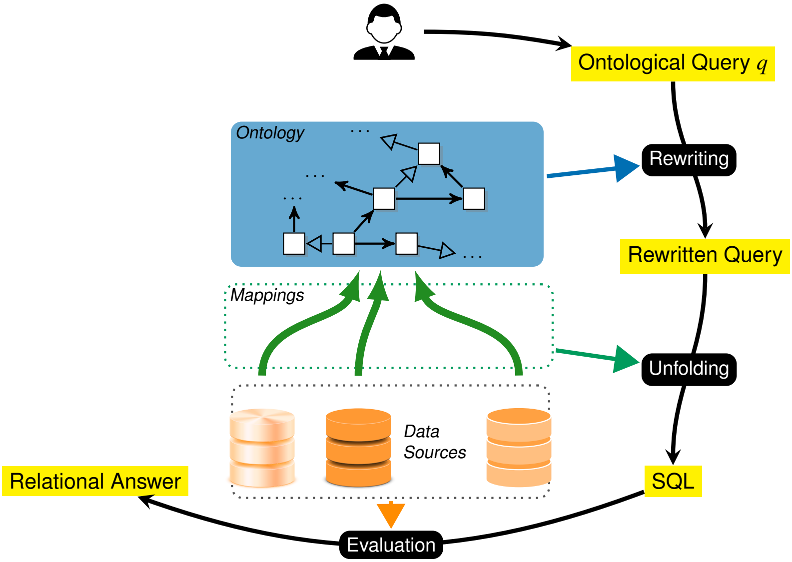

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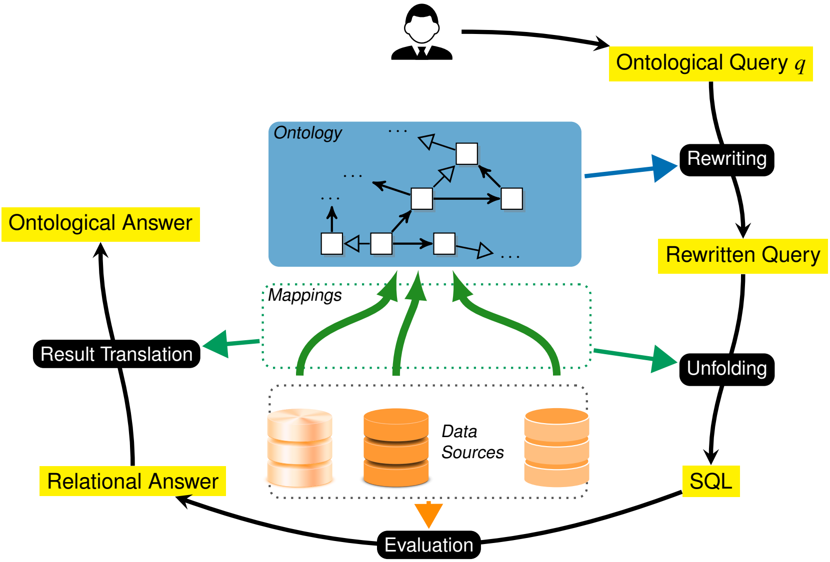

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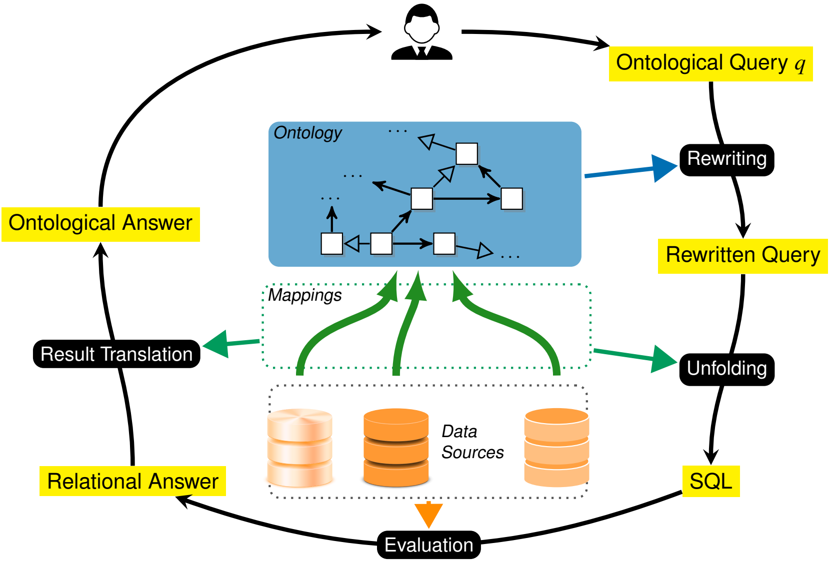

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Outline

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Query answering via query reformulation

To compute the certain answers to a SPARQL query q over an OBDA instance $\mathcal{O} = \langle \mathcal{P}, \mathcal{D} \rangle$, with $\mathcal{P} = \langle \mathcal{T}, \mathcal{S}, \mathcal{M} \rangle$:

1. Compute the perfect rewriting of q w.r.t. $\mathcal{T}$.
2. Unfold the perfect rewriting wrt the mapping $\mathcal{M}$.
3. Optimize the unfolded query, using database constraints.
4. Evaluate the resulting SQL query over $\mathcal{D}$.

Steps 1 – 3 are collectively called **query reformulation**.

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Steps 1 – 3 are collectively called **query reformulation**.

The rewriting Step 1 deals with the objects that are existentially implied by the axioms of the ontology.

Example of existential reasoning

Suppose that every graduate student is supervised by some professor, i.e.

$$\mathit{GraduateStudent} \sqsubseteq \exists \mathit{isSupervisedBy}.\mathit{Professor}$$

and john is a graduate student: $\mathit{GraduateStudent}(\mathtt{john})$.

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What is the answer to the following query?

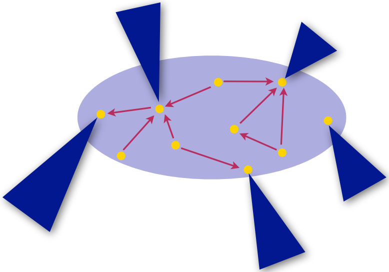
$$q(x) \leftarrow \mathit{isSupervisedBy}(x, y),\ \mathit{Professor}(y)$$

The answer should be `john`, even though we don't know who is John's supervisor (under existential reasoning).

Existential reasoning and query rewriting

Canonical model

Every consistent *DL-Lite* KB $\mathcal{K} = (\mathcal{T}, \mathcal{A})$ has a **canonical model** $\mathcal{I}_{\mathcal{K}}$, which **gives the right answers to all CQs**, i.e., cert$(q, \mathcal{K})$ = ans$(q, \mathcal{I}_{\mathcal{K}})$



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Core
individuals
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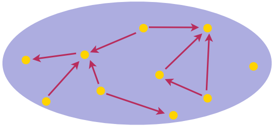

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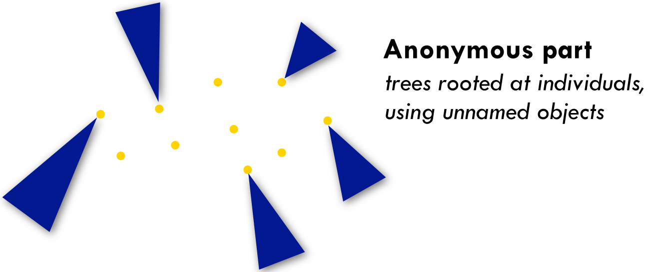

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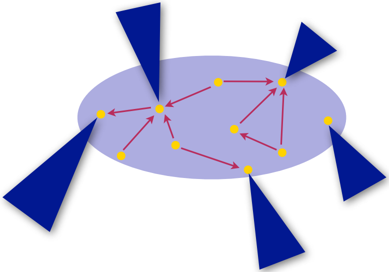

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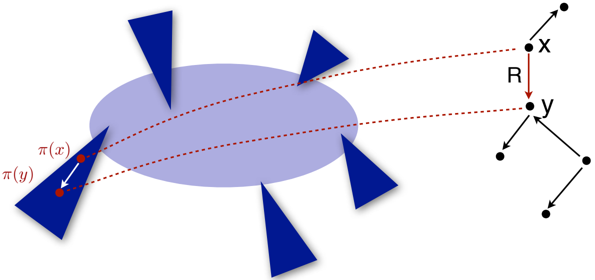

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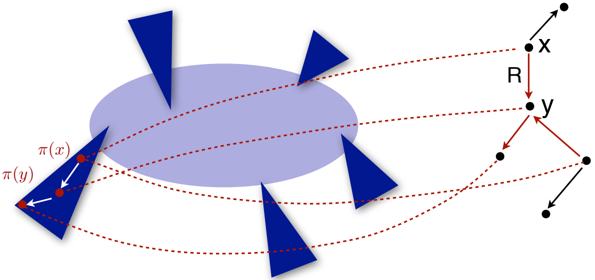

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Example of existential reasoning (continued)

Using the (tree witness) rewriting algorithm, the query

$$\mathit{q}(x) \leftarrow \mathit{isSupervisedBy}(x, y),\ \mathit{Professor}(y)$$

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Using the (tree witness) rewriting algorithm, the query

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is rewritten to a union of two conjunctive queries (or a SPARQL union query):

$$\begin{array}{lcl} q(x) & \leftarrow & \mathit{isSupervisedBy}(x, y),\ \mathit{Professor}(y) \\ q(x) & \leftarrow & \mathit{GraduateStudent}(x) \end{array}$$

Therefore, over the Abox $\mathit{GraduateStudent}(\texttt{john})$, the rewritten query returns $\texttt{john}$ as an answer.

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Therefore, over the Abox $\mathit{GraduateStudent}(\texttt{john})$, the rewritten query returns `john` as an answer.

Note: In *Ontop*, if one wants to answer queries by performing existential reasoning, the tree-witness rewriting algorithm needs to be switched on explicitly.

The *PerfectRef* algorithm for query rewriting

To illustrate Step 1 of the query reformulation algorithm, we briefly describe *PerfectRef*, a simple query rewriting algorithm that requires to iterate over:

- rewriting steps that involve TBox inclusion assertions, and
- unification of query atoms.

The perfect rewriting of q is still a SPARQL query involving `UNION`.

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Note: disjointness assertions play a role in ontology satisfiability, but can be ignored during query rewriting (i.e., we have **separability**).

Query rewriting step: Basic idea

Intuition: an inclusion assertion corresponds to a logic programming rule.

Example

The inclusion assertion $\mathit{FullProf} \sqsubseteq \mathit{Prof}$
corresponds to the logic programming rule $\mathit{Prof}(z) \leftarrow \mathit{FullProf}(z)$.

Query rewriting step: Basic idea

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Basic rewriting step:

When an atom in the query unifies with the **head** of the rule, generate a new query by substituting the atom with the **body** of the rule.

We say that the inclusion assertion **applies to** the atom.

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Consider the query $q(x) \leftarrow \mathit{Prof}(x)$.

By applying the inclusion assertion to the atom $\mathit{Prof}(x)$, we generate:

$$q(x) \leftarrow \mathit{FullProf}(x).$$

This query is added to the input query, and contributes to the perfect rewriting.

Query rewriting (cont'd)

Example

Consider the query $q(x) \leftarrow \mathit{teaches}(x, y), \mathit{Course}(y)$

and the inclusion assertion $\exists \mathit{teaches}^- \sqsubseteq \mathit{Course}$
as a logic programming rule: $\mathit{Course}(z_2) \leftarrow \mathit{teaches}(z_1, z_2)$.

The inclusion applies to $\mathit{Course}(y)$, and we add to the rewriting the query

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The inclusion applies to $\mathit{teaches}(x, y)$, and we add to the rewriting the query

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Query rewriting – Constants

Example

Conversely, for the query $\quad q(x) \leftarrow \mathit{teaches}(x, \mathtt{databases})$

and the same inclusion assertion as before $\quad \mathit{FullProf} \sqsubseteq \exists \mathit{teaches}$
as a logic programming rule: $\quad \mathit{teaches}(z, f(z)) \leftarrow \mathit{FullProf}(z)$

$\mathit{teaches}(x, \mathtt{databases})$ does not unify with $\mathit{teaches}(z, f(z))$, since the **skolem term** $f(z)$ in the head of the rule **does not unify** with the constant $\mathtt{databases}$.
Remember: We adopt the **unique name assumption**.

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We say that the inclusion does **not** apply to the atom $\mathit{teaches}(x, \mathtt{databases})$.

Example

The same holds for the following query, where y is **distinguished**, since unifying $f(z)$ with y would correspond to returning a skolem term as answer to the query:

$$q(x, y) \leftarrow \mathit{teaches}(x, y).$$

Query rewriting – Join variables

An analogous behavior to the one with constants and with distinguished variables holds when the atom contains **join variables** that would have to be unified with skolem terms.

Example

Consider the query $\quad q(x) \leftarrow \mathit{teaches}(x,y), \mathit{Course}(y)$

and the inclusion assertion $\quad \mathit{FullProf} \sqsubseteq \exists \mathit{teaches}$
as a logic programming rule: $\quad \mathit{teaches}(z, f(z)) \leftarrow \mathit{FullProf}(z)$.

The inclusion assertion above does **not** apply to the atom $\mathit{teaches}(x,y)$.

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Query rewriting – Reduce step

Example

Consider now the query $\quad q(x) \leftarrow \mathit{teaches}(x,y), \mathit{teaches}(z,y)$

and the inclusion assertion $\quad \mathit{FullProf} \sqsubseteq \exists\mathit{teaches}$

as a logic rule: $\quad \mathit{teaches}(z, f(z)) \leftarrow \mathit{FullProf}(z).$

This inclusion assertion does not apply to $\mathit{teaches}(x,y)$ or $\mathit{teaches}(z,y)$, since y is in join, and we would again introduce the skolem term in the rewritten query.

Query rewriting – Reduce step

Example

Consider now the query $q(x) \leftarrow teaches(x, y), teaches(z, y)$

and the inclusion assertion $FullProf \sqsubseteq \exists teaches$
as a logic rule: $teaches(z, f(z)) \leftarrow FullProf(z)$.

This inclusion assertion does not apply to $teaches(x, y)$ or $teaches(z, y)$, since y is in join, and we would again introduce the skolem term in the rewritten query.

Example

However, we can transform the above query by unifying the atoms $teaches(x, y)$ and $teaches(z, y)$.
This rewriting step is called **reduce**, and produces the query

$$q(x) \leftarrow teaches(x, y).$$

Now, we can apply the inclusion above, and add to the rewriting the query

$$q(x) \leftarrow FullProf(x).$$

Query rewriting – Summary

To compute the perfect rewriting of a query q, start from q, iteratively get a CQ q' to be processed, and do one of the following:

- Apply to some atom of q' an inclusion assertion in $\mathcal{T}$ as follows:

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\begin{array}{rccc}
A_1 \sqsubseteq A_2 & \ldots, A_2(x), \ldots & \leadsto & \ldots, A_1(x), \ldots \\
\exists P \sqsubseteq A & \ldots, A(x), \ldots & \leadsto & \ldots, P(x, \_), \ldots \\
\exists P^- \sqsubseteq A & \ldots, A(x), \ldots & \leadsto & \ldots, P(\_, x), \ldots \\
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P_1 \sqsubseteq P_2^- & \ldots, P_2(x, y), \ldots & \leadsto & \ldots, P_1(y, x), \ldots
\end{array}
$$

  ('_' denotes a variable that appears only once)

- Choose two atoms of q' that unify, and apply the unifier to q'.

Each time, the result of the above step is added to the queries to be processed.

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The UCQ resulting from this process is the **perfect rewriting** $r_{q,\mathcal{T}}$.

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Query rewriting algorithm

Algorithm *PerfectRef*$(Q, \mathcal{T}_P)$
Input: union of conjunctive queries Q, set $\mathcal{T}_P$ of *DL-Lite* inclusion assertions
Output: union of conjunctive queries PR
$PR := Q$;
repeat
  $PR' := PR$;
  for each $q \in PR'$ **do**
    for each g in q **do**
      for each inclusion assertion I in $\mathcal{T}_P$ **do**
        if I is applicable to g **then** $PR := PR \cup \{$ *ApplyPI*$(q, g, I) \}$;
    for each g_1, g_2 in q **do**
      if g_1 and g_2 unify **then** $PR := PR \cup \{\tau($*Reduce*$(q, g_1, g_2))\}$;
until $PR' = PR$;
return PR

Observations:

- Termination follows from having only finitely many different rewritings.
- Disjointness assertions and functionalities do not play any role in the rewriting of the query.

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Query answering in *DL-Lite* – Example

TBox:

$$\mathit{FullProf} \sqsubseteq \mathit{Prof}$$
$$\mathit{Prof} \sqsubseteq \exists \mathit{teaches}$$
$$\exists \mathit{teaches}^- \sqsubseteq \mathit{Course}$$

Corresponding rules:

$$\mathit{Prof}(x) \leftarrow \mathit{FullProf}(x)$$
$$\exists y(\mathit{teaches}(x,y)) \leftarrow \mathit{Prof}(x)$$
$$\mathit{Course}(x) \leftarrow \mathit{teaches}(y,x)$$

Query: $q(x) \leftarrow \mathit{teaches}(x,y), \mathit{Course}(y)$

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$q(x) \leftarrow \mathit{teaches}(x, y), \mathit{teaches}(\_, y)$

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Query answering in *DL-Lite* – Example

TBox:

$$\mathit{FullProf} \sqsubseteq \mathit{Prof}$$
$$\mathit{Prof} \sqsubseteq \exists \mathit{teaches}$$
$$\exists \mathit{teaches}^- \sqsubseteq \mathit{Course}$$

Corresponding rules:

$$\mathit{Prof}(x) \leftarrow \mathit{FullProf}(x)$$
$$\exists y(\mathit{teaches}(x,y)) \leftarrow \mathit{Prof}(x)$$
$$\mathit{Course}(x) \leftarrow \mathit{teaches}(y,x)$$

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ABox: $\mathit{teaches}(\mathtt{jim}, \mathtt{databases})$ $\quad \mathit{FullProf}(\mathtt{jim})$
$\mathit{teaches}(\mathtt{julia}, \mathtt{security})$ $\quad \mathit{FullProf}(\mathtt{nicole})$

Evaluating the perfect rewriting over the ABox (seen as a DB) produces as answer $\{\mathtt{jim}, \mathtt{julia}, \mathtt{nicole}\}$.

Query answering in *DL-Lite* – An interesting example

TBox: $\mathit{Person} \sqsubseteq \exists \mathit{hasFather}$
$\exists \mathit{hasFather}^- \sqsubseteq \mathit{Person}$

ABox: $\mathit{Person}(\mathtt{john})$

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Complexity of query answering in *DL-Lite*

Query answering for UCQs / SPARQL queries is:

- Efficiently tractable in the size of the TBox, i.e., PTime.
- Very efficiently tractable in the size of the ABox, i.e., AC^0.
- Exponential in the size of the **query**, more precisely NP-complete.

  In theory this is not bad, since this is precisely the complexity of evaluating CQs in plain relational DBs.

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Can we go beyond *DL-Lite*?

Essentially no! By adding essentially any additional DL constructor we lose first-order rewritability and hence these nice computational properties.

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Outline

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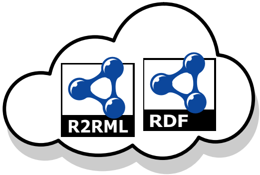
Querying the OBDA system

OBDA system $\mathcal{K} = \langle \mathcal{T}, \mathcal{M}, \mathcal{D} \rangle$

- *DL-Lite*$_{\mathcal{R}}$ TBox $\mathcal{T}$
- RDF graph $\mathcal{G}$ obtained from the mapping $\mathcal{M}$ and the data sources $\mathcal{D}$
- $\mathcal{G}$ can be viewed as the ABox



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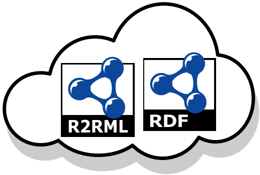

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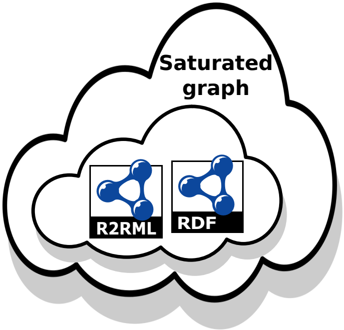

Saturated RDF graph $\mathcal{G}_{\text{sat}}$

- Saturation of $\mathcal{G}$ w.r.t. $\mathcal{T}$
- H-complete ABox

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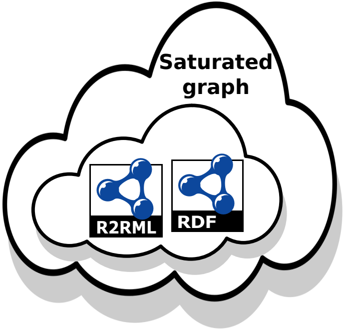
- SPARQL query q over $\mathcal{K}$
- If there is no existential restriction $B \sqsubseteq \exists R.C$ in $\mathcal{T}$, q can be directly evaluated over $\mathcal{G}_{\text{sat}}$



Saturated RDF graph $\mathcal{G}_{\text{sat}}$

- Saturation of $\mathcal{G}$ w.r.t. $\mathcal{T}$
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How to handle the RDF graph $\mathcal{G}_{\text{sat}}$ in practice?

By materializing it

- Materialization of $\mathcal{G}$ (ETL) + saturation
  - – Large volume
  - – Maintenance
- Typical profile: OWL 2 RL

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By keeping it virtual

- Query rewriting
- + No materialization required
- Saturated mapping $\mathcal{M}_{\text{sat}}$
- Typical profile: OWL 2 QL

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H-complete ABox

[Rodriguez-Muro, Kontchakov, and Zakharyaschev 2013; Kontchakov and Zakharyaschev 2014]

ABox saturation

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- Let $\mathcal{K}$ be a *DL-Lite*$_{\mathcal{R}}$ knowledge base, and let $\mathcal{K}_{\mathsf{sat}}$ be the result of saturating $\mathcal{K}$. Then, for every ABox assertion α, we have:

$$\mathcal{K} \models \alpha \qquad \text{iff} \qquad \alpha \in \mathcal{K}_{\mathsf{sat}}$$

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Saturated mapping $\mathcal{M}_{\mathsf{sat}}$ (also called *T-mapping*)

- Composition of the mapping $\mathcal{M}$ and the *DL-Lite*$_{\mathcal{R}}$ TBox $\mathcal{T}$.
- $\mathcal{M}_{\mathsf{sat}}$ applied to $\mathcal{D}$ produces $\mathcal{G}_{\mathsf{sat}}$ (H-complete ABox).

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- $\mathcal{M}_{\mathsf{sat}}$ applied to $\mathcal{D}$ produces $\mathcal{G}_{\mathsf{sat}}$ (H-complete ABox).
- Does not depend of the SPARQL query $\boldsymbol{q}$ (can be pre-computed).
- Can be optimized (exploiting query containment).

TBox, user-defined mapping assertions, and foreign key

$\mathit{Student} \sqsubseteq \mathit{Person}$	$\mathit{Student}(\textbf{iri1}(scode)) \leftsquigarrow \texttt{student}(scode, fn, ln)$	(1)
$\mathit{PostDoc} \sqsubseteq \mathit{Person}$	$\mathit{PostDoc}(\textbf{iri2}(acode)) \leftsquigarrow \texttt{academic}(acode, fn, ln, pos),\ pos = 9$	(2)
$\mathit{AssociateProfessor} \sqsubseteq \mathit{Person}$	$\mathit{AssociateProfessor}(\textbf{iri2}(acode)) \leftsquigarrow \texttt{academic}(acode, fn, ln, pos),\ pos = 2$	(3)
$\exists \mathit{teaches} \sqsubseteq \mathit{Person}$	$\mathit{FacultyMember}(\textbf{iri2}(acode)) \leftsquigarrow \texttt{academic}(acode, fn, ln, pos)$	(4)
	$\mathit{teaches}(\textbf{iri2}(acode), \textbf{iri3}(course)) \leftsquigarrow \texttt{teaching}(course, acode)$	(5)

FK: $\exists y_1.\texttt{teaching}(y_1, x) \rightarrow \exists y_2 y_3 y_4.\texttt{academic}(x, y_2, y_3, y_4)$

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By **saturating the mapping**, we obtain mapping assertions for *Person*

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By **optimizing the mapping** using query containment and the FK, we can remove mapping assertions 7, 8, and 10

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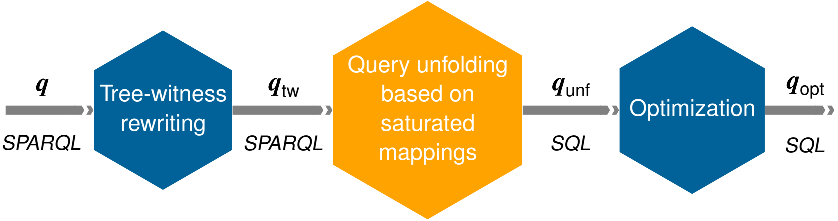
Outline

Query reformulation as implemented by Ontop



Step	Input	Output
1. Tree-witness rewriting	q (SPARQL) and $\mathcal{T}$	q_{tw} (SPARQL)
2. Query unfolding	q_{tw} and $\mathcal{M}_{sat}$	q_{unf} (SQL)
3. Query optimization	q_{unf}, primary and foreign keys	q_{opt} (SQL)

SQL query optimization

Objective : produce SQL queries that are . . .

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Integrity constraints

- Primary and foreign keys, unique constraints
- Sometimes implicit
- Vital for query reformulation!

Reformulation example – 1. Unfolding

Saturated mapping

$$\mathit{Teacher}(\mathbf{iri2}(acode)) \leadsto \texttt{academic}(acode, fn, ln, pos),\ pos \in [1..8]$$

$$\mathit{Teacher}(\mathbf{iri2}(acode)) \leadsto \texttt{teaching}(course, acode)$$

$$\mathit{firstName}(\mathbf{iri1}(scode), fn) \leadsto \texttt{student}(scode, fn, ln)$$

$$\mathit{firstName}(\mathbf{iri2}(acode), fn) \leadsto \texttt{academic}(acode, fn, ln, pos)$$

$$\mathit{lastName}(\mathbf{iri1}(scode), ln) \leadsto \texttt{student}(scode, fn, ln)$$

$$\mathit{lastName}(\mathbf{iri2}(acode), ln) \leadsto \texttt{academic}(acode, fn, ln, pos)$$

Query (we assume that the ontology is empty, hence $\boldsymbol{q}_{\mathrm{tw}} = \boldsymbol{q}$)

$$\boldsymbol{q}(x, y, z) \leftarrow \mathit{Teacher}(x),\ \mathit{firstName}(x, y),\ \mathit{lastName}(x, z)$$

Reformulation example – 1. Unfolding

Saturated mapping

$$\begin{aligned}
\mathit{Teacher}(\mathbf{iri2}(acode)) &\rightsquigarrow \mathtt{academic}(acode, fn, ln, pos),\\
&\quad\ pos \in [1..8]\\
\mathit{Teacher}(\mathbf{iri2}(acode)) &\rightsquigarrow \mathtt{teaching}(course, acode)\\
\mathit{firstName}(\mathbf{iri1}(scode), fn) &\rightsquigarrow \mathtt{student}(scode, fn, ln)\\
\mathit{firstName}(\mathbf{iri2}(acode), fn) &\rightsquigarrow \mathtt{academic}(acode, fn, ln, pos)\\
\mathit{lastName}(\mathbf{iri1}(scode), ln) &\rightsquigarrow \mathtt{student}(scode, fn, ln)\\
\mathit{lastName}(\mathbf{iri2}(acode), ln) &\rightsquigarrow \mathtt{academic}(acode, fn, ln, pos)
\end{aligned}$$

Query (we assume that the ontology is empty, hence $\boldsymbol{q}_{\mathsf{tw}} = \boldsymbol{q}$)

$$\boldsymbol{q}(x, y, z) \leftarrow \mathit{Teacher}(x),\ \mathit{firstName}(x, y),\ \mathit{lastName}(x, z)$$

Query unfolding

$$\begin{aligned}
\boldsymbol{q}_{\mathsf{unf}}(x, y, z) &\leftarrow \boldsymbol{q}1_{\mathsf{unf}}(x),\ \boldsymbol{q}2_{\mathsf{unf}}(x, y),\\
&\quad\ \boldsymbol{q}3_{\mathsf{unf}}(x, z)\\
\boldsymbol{q}1_{\mathsf{unf}}(\mathbf{iri2}(acode)) &\leftarrow \mathtt{academic}(acode, fn, ln, pos),\\
&\quad\ pos \in [1..8]\\
\boldsymbol{q}1_{\mathsf{unf}}(\mathbf{iri2}(acode)) &\leftarrow \mathtt{teaching}(course, acode)\\
\boldsymbol{q}2_{\mathsf{unf}}(\mathbf{iri1}(scode), fn) &\leftarrow \mathtt{student}(scode, fn, ln)\\
\boldsymbol{q}2_{\mathsf{unf}}(\mathbf{iri2}(acode), fn) &\leftarrow \mathtt{academic}(acode, fn, ln, pos)\\
\boldsymbol{q}3_{\mathsf{unf}}(\mathbf{iri1}(scode), ln) &\leftarrow \mathtt{student}(scode, fn, ln)\\
\boldsymbol{q}3_{\mathsf{unf}}(\mathbf{iri2}(acode), ln) &\leftarrow \mathtt{academic}(acode, fn, ln, pos)
\end{aligned}$$

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Reformulation example – 1. Unfolding

Saturated mapping

$$\begin{aligned}
\textit{Teacher}(\mathbf{iri2}(acode)) &\rightsquigarrow \texttt{academic}(acode, fn, ln, pos),\\
&\quad pos \in [1..8]\\
\textit{Teacher}(\mathbf{iri2}(acode)) &\rightsquigarrow \texttt{teaching}(course, acode)\\
\textit{firstName}(\mathbf{iri1}(scode), fn) &\rightsquigarrow \texttt{student}(scode, fn, ln)\\
\textit{firstName}(\mathbf{iri2}(acode), fn) &\rightsquigarrow \texttt{academic}(acode, fn, ln, pos)\\
\textit{lastName}(\mathbf{iri1}(scode), ln) &\rightsquigarrow \texttt{student}(scode, fn, ln)\\
\textit{lastName}(\mathbf{iri2}(acode), ln) &\rightsquigarrow \texttt{academic}(acode, fn, ln, pos)
\end{aligned}$$

Query (we assume that the ontology is empty, hence $\boldsymbol{q}_{\mathsf{tw}} = \boldsymbol{q}$)

$$\boldsymbol{q}(x, y, z) \leftarrow \textit{Teacher}(x),\ \textit{firstName}(x, y),\ \textit{lastName}(x, z)$$

Query unfolding, and **normalization**, to make the join conditions explicit

$$\begin{aligned}
\boldsymbol{q}_{\mathsf{norm}}(x, y, z) &\leftarrow \boldsymbol{q}1_{\mathsf{unf}}(x),\ \boldsymbol{q}2_{\mathsf{unf}}(x_1, y),\\
&\quad \boldsymbol{q}3_{\mathsf{unf}}(x_2, z),\ x = x_1,\ x = x_2\\
\boldsymbol{q}1_{\mathsf{unf}}(\mathbf{iri2}(acode)) &\leftarrow \texttt{academic}(acode, fn, ln, pos),\\
&\quad pos \in [1..8]\\
\boldsymbol{q}1_{\mathsf{unf}}(\mathbf{iri2}(acode)) &\leftarrow \texttt{teaching}(course, acode)\\
\boldsymbol{q}2_{\mathsf{unf}}(\mathbf{iri1}(scode), fn) &\leftarrow \texttt{student}(scode, fn, ln)\\
\boldsymbol{q}2_{\mathsf{unf}}(\mathbf{iri2}(acode), fn) &\leftarrow \texttt{academic}(acode, fn, ln, pos)\\
\boldsymbol{q}3_{\mathsf{unf}}(\mathbf{iri1}(scode), ln) &\leftarrow \texttt{student}(scode, fn, ln)\\
\boldsymbol{q}3_{\mathsf{unf}}(\mathbf{iri2}(acode), ln) &\leftarrow \texttt{academic}(acode, fn, ln, pos)
\end{aligned}$$

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Reformulation example – 2. Structural optimization

Unfolded normalized query

$$
\begin{aligned}
q_{\mathsf{norm}}(x,y,z) &\leftarrow q1_{\mathsf{unf}}(x),\ q2_{\mathsf{unf}}(x_1,y),\\
&\ q3_{\mathsf{unf}}(x_2,z),\\
&\ x = x_1,\ x = x_2\\
q1_{\mathsf{unf}}(\mathbf{iri2}(a)) &\leftarrow \mathtt{academic}(a,f,l,p),\\
&\ p \in [1..8]\\
q1_{\mathsf{unf}}(\mathbf{iri2}(a)) &\leftarrow \mathtt{teaching}(c,a)\\
q2_{\mathsf{unf}}(\mathbf{iri1}(s),f) &\leftarrow \mathtt{student}(s,f,l)\\
q2_{\mathsf{unf}}(\mathbf{iri2}(a),f) &\leftarrow \mathtt{academic}(a,f,l,p)\\
q3_{\mathsf{unf}}(\mathbf{iri1}(s),l) &\leftarrow \mathtt{student}(s,f,l)\\
q3_{\mathsf{unf}}(\mathbf{iri2}(a),l) &\leftarrow \mathtt{academic}(a,f,l,p)
\end{aligned}
$$

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Reformulation example – 2. Structural optimization

Unfolded normalized query

$$\begin{aligned}
\boldsymbol{q}_{\mathsf{norm}}(x,y,z) &\leftarrow \boldsymbol{q}1_{\mathsf{unf}}(x),\ \boldsymbol{q}2_{\mathsf{unf}}(x_1,y),\\
&\quad\ \boldsymbol{q}3_{\mathsf{unf}}(x_2,z),\\
&\quad\ x=x_1,\ x=x_2\\
\boldsymbol{q}1_{\mathsf{unf}}(\mathbf{iri2}(a)) &\leftarrow \mathtt{academic}(a,f,l,p),\\
&\quad\ p\in[1..8]\\
\boldsymbol{q}1_{\mathsf{unf}}(\mathbf{iri2}(a)) &\leftarrow \mathtt{teaching}(c,a)\\
\boldsymbol{q}2_{\mathsf{unf}}(\mathbf{iri1}(s),f) &\leftarrow \mathtt{student}(s,f,l)\\
\boldsymbol{q}2_{\mathsf{unf}}(\mathbf{iri2}(a),f) &\leftarrow \mathtt{academic}(a,f,l,p)\\
\boldsymbol{q}3_{\mathsf{unf}}(\mathbf{iri1}(s),l) &\leftarrow \mathtt{student}(s,f,l)\\
\boldsymbol{q}3_{\mathsf{unf}}(\mathbf{iri2}(a),l) &\leftarrow \mathtt{academic}(a,f,l,p)
\end{aligned}$$

Flattening (URI template lifting) – Part 1/2

$$\begin{aligned}
\boldsymbol{q}_{\mathsf{lift}}(\mathbf{iri2}(a),y,z) &\leftarrow \mathtt{academic}(a,f_1,l_1,p_1),\\
&\quad\ \mathtt{student}(s,f_2,l_2),\\
&\quad\ \mathtt{student}(s_1,f_3,l_3),\\
&\quad\ \mathbf{iri2}(a)=\mathbf{iri1}(s),\\
&\quad\ \mathbf{iri2}(a)=\mathbf{iri1}(s_1),\\
&\quad\ p_1\in[1..8]\\
\boldsymbol{q}_{\mathsf{lift}}(\mathbf{iri2}(a),y,z) &\leftarrow \mathtt{academic}(a,f_1,l_1,p_1),\\
&\quad\ \mathtt{student}(s,f_2,l_2),\\
&\quad\ \mathtt{academic}(a_2,f_3,z,p_3),\\
&\quad\ \mathbf{iri2}(a)=\mathbf{iri1}(s),\\
&\quad\ \mathbf{iri2}(a)=\mathbf{iri2}(a_2),\\
&\quad\ p_1\in[1..8]
\end{aligned}$$

(One sub-query not shown)

$$\begin{aligned}
\boldsymbol{q}_{\mathsf{lift}}(\mathbf{iri2}(a),y,z) &\leftarrow \mathtt{academic}(a,f_1,l_1,p_1),\\
&\quad\ \mathtt{academic}(a_1,y,l_2,p_2),\\
&\quad\ \mathtt{academic}(a_2,f_3,z,p_3),\\
&\quad\ \mathbf{iri2}(a)=\mathbf{iri2}(a_1),\\
&\quad\ \mathbf{iri2}(a)=\mathbf{iri2}(a_2),\\
&\quad\ p_1\in[1..8]
\end{aligned}$$

Reformulation example – 2. Structural optimization

Unfolded normalized query

$$
\begin{aligned}
\boldsymbol{q}_{\text{norm}}(x,y,z) &\leftarrow \boldsymbol{q}1_{\text{unf}}(x),\ \boldsymbol{q}2_{\text{unf}}(x_1,y),\\
&\ \boldsymbol{q}3_{\text{unf}}(x_2,z),\\
&\ x = x_1,\ x = x_2\\
\boldsymbol{q}1_{\text{unf}}(\textbf{iri2}(a)) &\leftarrow \texttt{academic}(a,f,l,p),\\
&\ p \in [1..8]\\
\boldsymbol{q}1_{\text{unf}}(\textbf{iri2}(a)) &\leftarrow \texttt{teaching}(c,a)\\
\boldsymbol{q}2_{\text{unf}}(\textbf{iri1}(s),f) &\leftarrow \texttt{student}(s,f,l)\\
\boldsymbol{q}2_{\text{unf}}(\textbf{iri2}(a),f) &\leftarrow \texttt{academic}(a,f,l,p)\\
\boldsymbol{q}3_{\text{unf}}(\textbf{iri1}(s),l) &\leftarrow \texttt{student}(s,f,l)\\
\boldsymbol{q}3_{\text{unf}}(\textbf{iri2}(a),l) &\leftarrow \texttt{academic}(a,f,l,p)
\end{aligned}
$$

- While flattening, we can avoid to generate those queries that contain in their body an equality between two terms with incompatible IRI templates.
- This might avoid a potential exponential blowup.

Flattening (URI template lifting) – Part 2/2

$$
\begin{aligned}
\boldsymbol{q}_{\text{lift}}(\textbf{iri2}(a),y,z) &\leftarrow \texttt{teaching}(c,a),\\
&\ \texttt{student}(s,f_2,l_2),\\
&\ \texttt{student}(s_1,f_3,l_3),\\
&\ \textbf{iri2}(a) = \textbf{iri1}(s),\\
&\ \textbf{iri2}(a) = \textbf{iri1}(s_1)
\end{aligned}
$$

$$
\begin{aligned}
\boldsymbol{q}_{\text{lift}}(\textbf{iri2}(a),y,z) &\leftarrow \texttt{teaching}(c,a),\\
&\ \texttt{student}(s,f_2,l_2),\\
&\ \texttt{academic}(a_2,f_3,z,p_3),\\
&\ \textbf{iri2}(a) = \textbf{iri1}(s),\\
&\ \textbf{iri2}(a) = \textbf{iri2}(a_2)
\end{aligned}
$$

(One sub-query not shown)

$$
\begin{aligned}
\boldsymbol{q}_{\text{lift}}(\textbf{iri2}(a),y,z) &\leftarrow \texttt{teaching}(c,a),\\
&\ \texttt{academic}(a_1,y,l_2,p_2),\\
&\ \texttt{academic}(a_2,f_3,z,p_3),\\
&\ \textbf{iri2}(a) = \textbf{iri2}(a_1),\\
&\ \textbf{iri2}(a) = \textbf{iri2}(a_2)
\end{aligned}
$$

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Reformulation example – 3. Semantic optimization

We are left with just two queries

$$\begin{array}{rcl} \boldsymbol{q}_{\mathsf{lift}}(\mathbf{iri2}(a), y, z) & \leftarrow & \mathtt{academic}(a, f_1, l_1, p_1),\ \ p_1 \in [1..8], \\ & & \mathtt{academic}(a_1, y, l_2, p_2),\ \mathbf{iri2}(a) = \mathbf{iri2}(a_1), \\ & & \mathtt{academic}(a_2, f_3, z, p_3),\ \mathbf{iri2}(a) = \mathbf{iri2}(a_2) \\ \boldsymbol{q}_{\mathsf{lift}}(\mathbf{iri2}(a), y, z) & \leftarrow & \mathtt{teaching}(c, a), \\ & & \mathtt{academic}(a_1, y, l_2, p_2),\ \mathbf{iri2}(a) = \mathbf{iri2}(a_1), \\ & & \mathtt{academic}(a_2, f_3, z, p_3),\ \mathbf{iri2}(a) = \mathbf{iri2}(a_2) \end{array}$$

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Reformulation example – 3. Semantic optimization

We are left with just two queries, that we can simplify by eliminating equalities

$$\begin{array}{rcl} q_{\text{struct}}(\textbf{iri2}(a), y, z) & \leftarrow & \texttt{academic}(a, f_1, l_1, p_1),\ \ p_1 \in [1..8], \\ & & \texttt{academic}(a, y, l_2, p_2), \\ & & \texttt{academic}(a, f_3, z, p_3) \\ q_{\text{struct}}(\textbf{iri2}(a), y, z) & \leftarrow & \texttt{teaching}(c, a), \\ & & \texttt{academic}(a, y, l_2, p_2), \\ & & \texttt{academic}(a, f_3, z, p_3) \end{array}$$

Reformulation example – 3. Semantic optimization

We are left with just two queries, that we can simplify by eliminating equalities

$$\begin{array}{rcl} q_{\text{struct}}(\textbf{iri2}(a), y, z) & \leftarrow & \texttt{academic}(a, f_1, l_1, p_1),\;\; p_1 \in [1..8], \\ & & \texttt{academic}(a, y, l_2, p_2), \\ & & \texttt{academic}(a, f_3, z, p_3) \end{array}$$

$$\begin{array}{rcl} q_{\text{struct}}(\textbf{iri2}(a), y, z) & \leftarrow & \texttt{teaching}(c, a), \\ & & \texttt{academic}(a, y, l_2, p_2), \\ & & \texttt{academic}(a, f_3, z, p_3) \end{array}$$

We can then exploit database constraints (e.g., primary keys) for semantic optimization of the query.

Self-join elimination (semantic optimization)

PK: $\texttt{academic}(acode, f, l, p) \land \texttt{academic}(acode, f', l', p')$
$$\rightarrow (f = f') \land (l = l') \land (p = p')$$

Reformulation example – 3. Semantic optimization

We are left with just two queries, that we can simplify by eliminating equalities

$$\begin{aligned} q_{\text{struct}}(\textbf{iri2}(a), y, z) \leftarrow\ & \texttt{academic}(a, f_1, l_1, p_1),\ p_1 \in [1..8], \\ & \texttt{academic}(a, y, l_2, p_2), \\ & \texttt{academic}(a, f_3, z, p_3) \end{aligned}$$

$$\begin{aligned} q_{\text{struct}}(\textbf{iri2}(a), y, z) \leftarrow\ & \texttt{teaching}(c, a), \\ & \texttt{academic}(a, y, l_2, p_2), \\ & \texttt{academic}(a, f_3, z, p_3) \end{aligned}$$

We can then exploit database constraints (e.g., primary keys) for semantic optimization of the query.

Self-join elimination (semantic optimization)

PK: $\texttt{academic}(acode, f, l, p) \land \texttt{academic}(acode, f', l', p') \rightarrow (f = f') \land (l = l') \land (p = p')$

$$q_{\text{opt}}(\textbf{iri2}(a), y, z) \leftarrow \texttt{academic}(a, y, z, p_1),\ p_1 \in [1..8]$$

$$q_{\text{opt}}(\textbf{iri2}(a), y, z) \leftarrow \texttt{teaching}(c, a),\ \texttt{academic}(a, y, z, p_2)$$

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