Ontological Conjunctive Query Answering over Large Knowledge Bases

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Université Montpellier 2

April 16, 2011
1. Research problem

2. Encodings & Translations

3. Current work

4. Conclusion

5. Questions
## Table of Contents

1. Research problem
2. Encodings & Translations
3. Current work
4. Conclusion
5. Questions
Research problem

(1) Ontological conjunctive query answering

Decision problem
Research problem

(1) **Ontological conjunctive query answering**

Knowledge base

Decision problem
(1) **Ontological conjunctive query answering**

Factual knowledge
(Very often a DB)

Knowledge base
Research problem

(1) **Ontological conjunctive query answering**

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Knowledge base

Decision problem
Research problem

(1) **Ontological conjunctive query answering**

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Knowledge base

Decision problem

(1) “Is there an answer to the query in the knowledge base”?
Research problem

(1) **Ontological conjunctive query answering**

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Knowledge base

(2) **Logical form**

<table>
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<tr>
<th>Logical fact $\mathcal{F}$</th>
<th>Ontology $\mathcal{O}$</th>
<th>Query $\mathcal{Q}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Conjunction of atoms)</td>
<td>($\forall \exists$-rules)</td>
<td>(Conjunctive query)</td>
</tr>
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</table>

Decision problem

(1) “Is there an answer to the query in the knowledge base”?
Research problem

(1) **Ontological conjunctive query answering**

- **Factual knowledge** (Very often a DB)
- **Ontology** (Universal knowledge)
- **Query** (Conjunctive query)

**Knowledge base**

(2) **Logical form**

- **Logical fact** $\mathcal{F}$ (Conjunction of atoms)
- **Ontology** $\mathcal{O}$ ($\forall\exists$-rules)
- **Query** $\mathcal{Q}$ (Conjunctive query)

Decision problem

(1) "Is there an answer to the query in the knowledge base"?

(2) $\{\mathcal{F}, \mathcal{O}\} \models \mathcal{Q}$?
Research problem

\[ \mathcal{F} \models Q \]

... iff there is a substitution \( S \) associating every term of the query to a term in the facts.

Problem: Finding substitutions
(Also known as ENTAILMENT)
Research problem

$\mathcal{F} \models Q$

... iff there is a substitution $S$ associating every term of the query to a term in the facts.

Problem: Finding substitutions
(Also known as ENTAILMENT)

$\{\mathcal{F}, \mathcal{O}\} \models Q$

... iff after being enriched by $\mathcal{O}$, there is a substitution $S$ associating every term of the query to a term in the facts.

Problem: Applying rules, Finding substitutions
(Also known as RULE-ENTAILMENT)
Rules

A rule contains two different parts: **hypothesis** and **conclusion**.

**Example**

```
∀ x, y, z co-worker (x, y) ∧ co-worker (y, z) → co-worker (x, z)
```

Rules semantics are that anytime the hypothesis of a rule is found in the facts, its conclusion is then added to the KB as new information.
A rule contains two different parts: **hypothesis** and **conclusion**.

**Example**

“If $x$ and $y$ are co-workers, and $y$ and $z$ are co-workers, then $x$ and $z$ are also co-workers”

$$\forall x, y, z \text{ co-worker}(x, y) \land \text{co-worker}(y, z) \rightarrow \text{co-worker}(x, z)$$

Rules semantics are that anytime the hypothesis of a rule is found in the facts, its conclusion is then added to the KB as new information.
Finding substitutions

**Example**

**Facts:**

\[
\begin{align*}
\text{works-for}(\text{Mark}, \text{LIRMM}) & \land \\
\text{works-for}(\text{Travis}, \text{LIRMM}) & \land \\
\text{works-for}(\text{Tom}, \text{LIRMM}) & \land \\
\text{plays-for}(\text{Mark}, \text{Team A}) & \land \\
\text{plays-for}(\text{Travis}, \text{Team B}) & \land \\
\text{plays-for}(\text{Tom}, \text{Team C}) & \land \\
\text{is-a}(\text{Team A}, \text{SquashClub}) & \land \\
\text{is-a}(\text{Team B}, \text{RugbyClub}) & \land \\
\text{is-a}(\text{Team C}, \text{SquashClub}) & \land 
\end{align*}
\]

**Rules:**

\[
\begin{align*}
\forall x, y, z \ \text{works-for}(x, z) & \land \text{works-for}(y, z) \rightarrow \text{co-worker}(x, y) \\
\forall x, y \ \text{plays-for}(x, y) & \land \text{is-a}(y, \text{SquashClub}) \rightarrow \text{plays}(x, \text{Squash}) \\
\forall x, y, z \ \text{plays}(x, z) & \land \text{plays}(y, z) \rightarrow \text{same-sport}(x, y)
\end{align*}
\]

**Q1:** \( \exists x \ \text{plays-for}(x, \text{Team B}) \)

**Q2:** \( \exists x, y \ \text{co-worker}(x, y) \land \text{same-sport}(x, y) \)
Finding substitutions

**Example**

**Facts:**

\( \text{works-for}(\text{Mark}, \text{LIRMM}) \land \)
\( \text{works-for}(\text{Travis}, \text{LIRMM}) \land \)
\( \text{works-for}(\text{Tom}, \text{LIRMM}) \land \)
\( \text{plays-for}(\text{Mark}, \text{Team A}) \land \)
\( \text{plays-for}(\text{Travis}, \text{Team B}) \land \)
\( \text{plays-for}(\text{Tom}, \text{Team C}) \land \)
\( \text{is-a}(\text{Team A}, \text{SquashClub}) \land \)
\( \text{is-a}(\text{Team B}, \text{RugbyClub}) \land \)
\( \text{is-a}(\text{Team C}, \text{SquashClub}) \land \)

**Rules:**

\( \forall x, y, z \ \text{works-for}(x, z) \land \text{works-for}(y, z) \rightarrow \text{co-worker}(x, y) \)
\( \forall x, y \ \text{plays-for}(x, y) \land \text{is-a}(y, \text{SquashClub}) \rightarrow \text{plays}(x, \text{Squash}) \)
\( \forall x, y, z \ \text{plays}(x, z) \land \text{plays}(y, z) \rightarrow \text{same-sport}(x, y) \)

**Q1:** \( \exists x \ \text{plays-for}(x, \text{Team B}) \)
**Answers:** \( \{(x, \text{Travis})\} \)

**Q2:** \( \exists x, y \ \text{co-worker}(x, y) \land \text{same-sport}(x, y) \)
Queries and rule application

Q2: \( \exists x, y \text{ co-worker}(x, y) \land \text{same-sport}(x, y) \)

R1: \( \forall x, y, z \text{ works-for}(x, z) \land \text{works-for}(y, z) \rightarrow \text{co-worker}(x, y) \)

R2: \( \forall x, y \text{ plays-for}(x, y) \land \text{is-a}(y, \text{SquashClub}) \rightarrow \text{plays}(x, \text{Squash}) \)

R3: \( \forall x, y, z \text{ plays}(x, z) \land \text{plays}(y, z) \rightarrow \text{same-sport}(x, y) \)

Fact

\text{works-for}(\text{Mark}, \text{LIRMM})
\text{works-for}(\text{Travis}, \text{LIRMM})
\text{works-for}(\text{Tom}, \text{LIRMM})

\text{plays-for}(\text{Mark}, \text{Team A})
\text{plays-for}(\text{Travis}, \text{Team B})
\text{plays-for}(\text{Tom}, \text{Team C})

\text{is-a}(\text{Team A, SquashClub})
\text{is-a}(\text{Team B, RugbyClub})
\text{is-a}(\text{Team C, SquashClub})
Queries and rule application

Q2: $\exists x, y \ co-worker(x, y) \land same-sport(x, y)$

R1: $\forall x, y, z works-for(x, z) \land works-for(y, z) \rightarrow co-worker(x, y)$

R2: $\forall x, y plays-for(x, y) \land is-a(y, SquashClub) \rightarrow plays(x, Squash)$

R3: $\forall x, y, z plays(x, z) \land plays(y, z) \rightarrow same-sport(x, y)$

Fact

$\text{works-for}(Mark, LIRMM)$
$\text{works-for}(Travis, LIRMM)$
$\text{works-for}(Tom, LIRMM)$
$\text{plays-for}(Mark, Team A)$
$\text{plays-for}(Travis, Team B)$
$\text{plays-for}(Tom, Team C)$
$\text{is-a}(Team A, SquashClub)$
$\text{is-a}(Team B, RugbyClub)$
$\text{is-a}(Team C, SquashClub)$

$\text{co-worker}(Mark, Travis)$
$\text{co-worker}(Mark, Tom)$
$\text{co-worker}(Travis, Mark)$
$\text{co-worker}(Travis, Tom)$
$\text{co-worker}(Tom, Mark)$
$\text{co-worker}(Tom, Travis)$
Queries and rule application

**Q2**: \( \exists x, y \ co-worker(x, y) \land same-sport(x, y) \)

**R1**: \( \forall x, y, z \ works-for(x, z) \land works-for(y, z) \rightarrow co-worker(x, y) \)

**R2**: \( \forall x, y \ plays-for(x, y) \land is-a(y, SquashClub) \rightarrow plays(x, Squash) \)

**R3**: \( \forall x, y, z \ plays(x, z) \land plays(y, z) \rightarrow same-sport(x, y) \)

**Fact**

<table>
<thead>
<tr>
<th>Fact 1</th>
<th>Fact 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>works-for(Mark, LIRMM)</td>
<td>co-worker(Mark, Travis)</td>
</tr>
<tr>
<td>works-for(Travis, LIRMM)</td>
<td>co-worker(Mark, Tom)</td>
</tr>
<tr>
<td>works-for(Tom, LIRMM)</td>
<td>co-worker(Travis, Mark)</td>
</tr>
<tr>
<td>plays-for(Mark, Team A)</td>
<td>co-worker(Travis, Tom)</td>
</tr>
<tr>
<td>plays-for(Travis, Team B)</td>
<td>co-worker(Tom, Mark)</td>
</tr>
<tr>
<td>plays-for(Tom, Team C)</td>
<td>co-worker(Tom, Travis)</td>
</tr>
<tr>
<td>is-a(Team A, SquashClub)</td>
<td>plays(Mark, Squash)</td>
</tr>
<tr>
<td>is-a(Team B, RugbyClub)</td>
<td>plays(Tom, Squash)</td>
</tr>
<tr>
<td>is-a(Team C, SquashClub)</td>
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Ontological Conjunctive Query Answering over Large Knowledge Bases
PAIVA LIMA DA SILVA Bruno (Université Montpellier 2)
Research problem: Encodings & Translations  
Current work:  
Conclusion:  
Questions:  

Queries and rule application

Q2: \( \exists x, y \ co-worker(x, y) \land same-sport(x, y) \)

R1: \( \forall x, y, z \ works-for(x, z) \land works-for(y, z) \rightarrow co-worker(x, y) \)

R2: \( \forall x, y \ plays-for(x, y) \land is-a(y, SquashClub) \rightarrow plays(x, Squash) \)

R3: \( \forall x, y, z \ plays(x, z) \land plays(y, z) \rightarrow same-sport(x, y) \)

Fact

\[\begin{align*}
\text{works-for}(Mark, LIRMM) & \quad \text{co-worker}(Mark, Travis) \\
\text{works-for}(Travis, LIRMM) & \quad \text{co-worker}(Mark, Tom) \\
\text{works-for}(Tom, LIRMM) & \quad \text{co-worker}(Travis, Mark) \\
\text{plays-for}(Mark, Team A) & \quad \text{co-worker}(Travis, Tom) \\
\text{plays-for}(Travis, Team B) & \quad \text{co-worker}(Tom, Mark) \\
\text{plays-for}(Tom, Team C) & \quad \text{co-worker}(Tom, Travis) \\
\text{is-a}(Team A, SquashClub) & \quad \text{plays}(Mark, Squash) \\
\text{is-a}(Team B, RugbyClub) & \quad \text{plays}(Tom, Squash) \\
\text{is-a}(Team C, SquashClub) & \quad \text{same-sport}(Mark, Tom) \\
\text{same-sport}(Tom, Mark) & \\
\end{align*}\]
Queries and rule application

Q2: $\exists x, y \ co\text{-}worker(x, y) \land same\text{-}sport(x, y)$

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Fact

works-for(Mark, LIRMM)  co-worker(Mark, Travis)
works-for(Travis, LIRMM)  co-worker(Mark, Tom)
works-for(Tom, LIRMM)  co-worker(Travis, Mark)
plays-for(Mark, Team A)  co-worker(Travis, Tom)
plays-for(Travis, Team B)  co-worker(Tom, Mark)
plays-for(Tom, Team C)  co-worker(Tom, Travis)
is-a(Team A, SquashClub)  plays(Mark, Squash)
is-a(Team B, RugbyClub)  plays(Tom, Squash)
is-a(Team C, SquashClub)  same-sport(Mark, Tom)

Answers: $\{(x,\text{Mark}), (y,\text{Tom})\} \& \{(x,\text{Tom}), (y,\text{Mark})\}$
Goals & Challenges

We focus our work on finding substitutions between terms from a given query (constants or variables) and the terms from our facts.

In order to do it, we use a BackTrack algorithm.

Different methods for KR and manipulation by dedicated reasoning systems have been successfully studied in the past.
Goals & Challenges

We focus our work on finding substitutions between terms from a given query (constants or variables) and the terms from our facts.

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Different methods for KR and manipulation by dedicated reasoning systems have been successfully studied in the past.

Large knowledge bases: New challenge

- $F$ can be very large (see the Semantic Web)
- Large $\rightarrow$ Does not fit in main memory.
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Different methods for KR and manipulation by dedicated reasoning systems have been successfully studied in the past.

**Large** knowledge bases: New challenge

- $F$ can be very large (see the Semantic Web)
- Large $\rightarrow$ Does not fit in main memory.

"Can we have efficiently an answer to $Q$, when $F$ is very large?"
Table of Contents

1 Research problem

2 Encodings & Translations

3 Current work

4 Conclusion

5 Questions
Encoding: Fact → Set

Encoding the fact from our example:

- works for (Mark, LIRMM)
- works for (Travis, LIRMM)
- works for (Tom, LIRMM)
- plays for (Mark, Team A)
- plays for (Travis, Team B)
- plays for (Tom, Team C)
- is a (Team A, SquashClub)
- is a (Team B, RugbyClub)
- is a (Team C, SquashClub)
Encoding: Fact → Set

Encoding the fact from our example:

\{ \text{works-for}(Mark, LIRMM), \text{works-for}(Travis, LIRMM), \\
\text{works-for}(Tom, LIRMM), \text{plays-for}(Mark, Team A), \text{plays-for}(Travis, Team B), \\
\text{plays-for}(Tom, Team C), \text{is-a}(Team A, SquashClub), \\
\text{is-a}(Team B, RugbyClub), \text{is-a}(Team C, SquashClub) \} \\

- Encoded yes, however totally unstructured.
- The complexity of every atomic operation depend on the size of the knowledge base in atoms.
Encoding: Fact → Tables

Structuring our fact by the atoms predicates, we obtain tables:
Structuring our fact by the atoms predicates, we obtain **tables**:

- **works-for**: Table 1
  - Mark: LIRMM
  - Travis: LIRMM
  - Tom: LIRMM

- **plays-for**: Table 2
  - Mark: Team A
  - Travis: Team B
  - Tom: Team C

- **is-a**: Table 1
  - Team A: SquashClub

- Team B: RugbyClub

- Team C: SquashClub

- This encoding can be directly stored in a Relational Database.
- Querying is then available either with BackTrack, either with a SQL interface.
Encoding: Fact $\rightarrow$ Graph

Structuring the fact, this time by its terms, we obtain a graph:
Encoding: Fact $\rightarrow$ Graph

Structuring the fact, this time by its terms, we obtain a graph:
Encoding a fact without a structure is totally inappropriate for our problem.
Analysis

- Encoding a fact without a structure is totally inappropriate for our problem.

- Relational Databases handle very well knowledge located in secondary memory, however:
  - Atomic operations of the BackTrack use SQL operations which complexity also depend on the size of the tables.
  - Using SQL instead may also not be the best solution: Joins become very costly as the number of predicates increases.
Analysis

- Encoding a fact without a structure is totally inappropriate for our problem.

- Relational Databases handle very well knowledge located in secondary memory, however:
  - Atomic operations of the BackTrack use SQL operations which complexity also depend on the size of the tables.
  - Using SQL instead may also not be the best solution: Joins become very costly as the number of predicates increases.

- Running the BackTrack algorithm with a graph works very well when the graph is stored in main memory. Unfortunately, it does not scale very well.
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Current challenges

In order to be able to perform reasoning over very large knowledge bases, we started searching for storage systems:
Current challenges

In order to be able to perform reasoning over very large knowledge bases, we started searching for storage systems:

- that have the ability to support very large knowledge bases stored in secondary memory.
Current challenges

In order to be able to perform reasoning over very large knowledge bases, we started searching for storage systems:

- that have the ability to support very large knowledge bases stored in secondary memory.
- efficient on homomorphism elementar operations, such as:
  - computing & retrieving the neighbourhood of a term and to be able to iterate over this structure.
  - checking whether there is a given relation between two given nodes or not.
In order to be able to perform reasoning over very large knowledge bases, we started searching for storage systems:

- that have the ability to support very large knowledge bases stored in secondary memory.
- efficient on homomorphism elementary operations, such as:
  - computing & retrieving the neighbourhood of a term and to be able to iterate over this structure.
  - checking whether there is a given relation between two given nodes or not.
- in which the complexity (time) of the insertion of a new atom does not depend on the size of the KB.
Alaska Project:

Abstract Logic-based Architecture for Storage systems & Knowledge bases Analysis

- Implementation of classes and interfaces that ensure that all the storage systems plugged in will answer to the same methods using a common type of data.
- Written in JAVA: Very easy to plug several pieces of code in, however, with a significant loss in speed and efficiency.
Alaska: Architecture

**Figure:** Class diagram for the architecture.
Application #1

Comparing storage systems between themselves:

\[ \mathcal{F} \models Q \]

Abstract Architecture

Relational DB

Graph DB
Application #1

Comparing storage systems between themselves:

$$\mathcal{F} \models Q$$

Abstract Architecture

Relational DB

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Application #1

Comparing storage systems between themselves:

\[ F \models Q \]

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Abstract Architecture

Relational DB

Graph DB
Application #1

Comparing storage systems between themselves:

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Abstract Architecture

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Test results

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<th>Name</th>
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<th>Querying time</th>
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<tr>
<td>RDB</td>
<td>... Mb</td>
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Abstract Architecture

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Application #2

Comparing different querying interfaces for a same storage system:

\[ F \models Q \]

Abstract Architecture

Relational DB  Graph DB
Comparing different querying interfaces for a same storage system:

\[ \mathcal{F} \models Q \]

- Abstract Architecture
- Relational DB
- Graph DB
Application #2

Comparing different querying interfaces for a same storage system:

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Abstract Architecture

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Application #2

Comparing different querying interfaces for a same storage system:

\[ \mathcal{F} \models Q \]

\( Q \rightarrow \text{SQL} \)

\( \text{Abstract Architecture} \)

\( \text{Relational DB} \)

\( \text{Graph DB} \)

Test results

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<tr>
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Implementations currently supported by the Alaska project.

Next step: Which kind of data to use?
Implementations currently supported by the Alaska project.

Abstract Architecture

Relational Databases

Graph Implementations

SQLite
MySQL
*dex
OrientDB
HyperGraphDB
Neo4j
Blueprints

Next step: Which kind of data to use?
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1 Research problem
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4 Conclusion
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Future work

As the execution performance also came into play in our research problem, our future work will consist in:

- finding and plugging more pertinent storage systems into our system.
- identifying any other problems that might have an influence when querying over large knowledge bases.
- running tests against several large knowledge bases available throughout the web.
- identifying the storage methods that answer best our problem, and where improvements can be made.
Then after...

We will also consider working on:

- implementing some kind of knowledge generator that would generate unbiased facts, which we could test against real data.
- optimizing our BackTrack algorithm in order to enhance the performance of our system.
- perhaps implementing a rule application system in order to tackle the RULE-ENTAILMENT problem.
# Table of Contents

1. Research problem
2. Encodings & Translations
3. Current work
4. Conclusion
5. Questions
Questions

Thank you!

Questions & comments...