Ontology-mediated query answering over temporal data: A Survey

(arXiv.org: https://arxiv.org/abs/2004.07221)

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Joint work with

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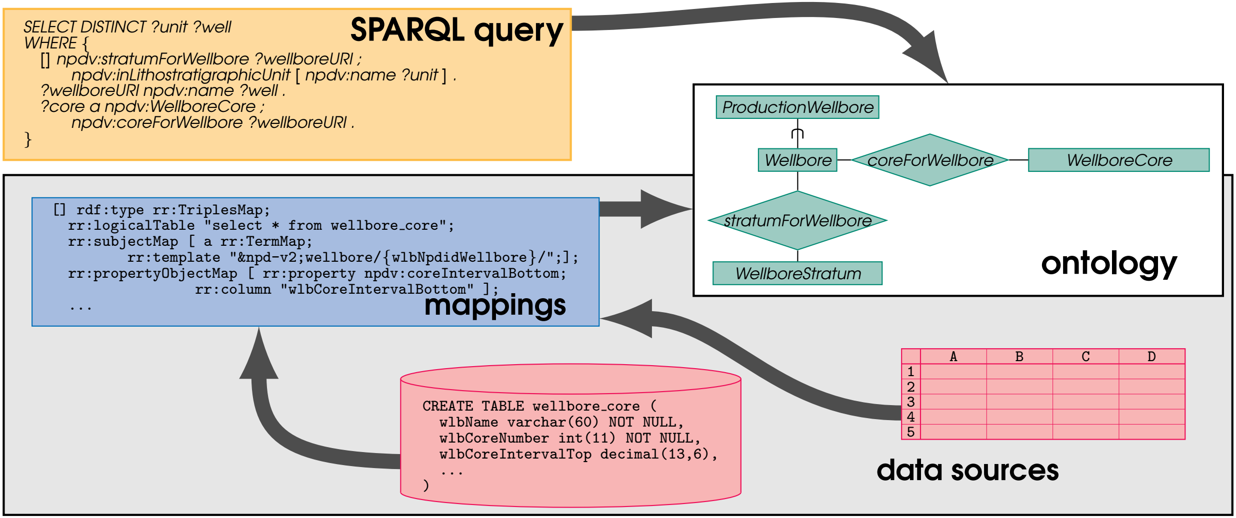
KRDB Summer Online Seminars 2020 - 8 May

Ontology-based data access (OBDA)

(the Romans ≈ **2007**)



Ontology – gives a high-level conceptual view of the data
– provides a convenient & natural vocabulary for user queries
– facilitates data integration via a global schema

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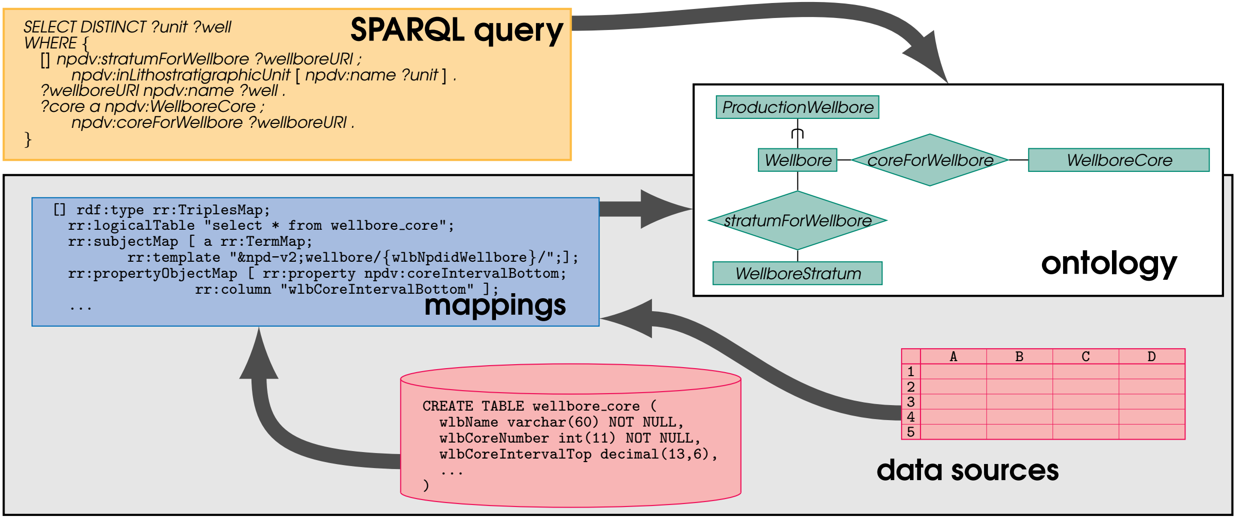

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OWL 2 QL ontology-mediated queries $(\mathcal{O}, q(\vec{x}))$ are FO-rewritable

reduction to DB query evaluation $\exists q' \; \forall \mathcal{D}, \vec{a} \quad \mathcal{O}, \mathcal{D} \models q(\vec{a}) \iff \mathcal{D} \models q'(\vec{a})$

Research problems

1. Which temporal logics and query languages are suitable for temporal OBDA as far as their expressive power is concerned?

2. Investigate expressivity and computational properties of the temporal Ontology languages (Satisfiability, Logical Implication, etc.)

3. Classify temporal languages by the type of rewritability (FO, datalog, etc.) and data complexity of OMQ answering

4. Devise algorithms, implementations, experiments, use cases

5. Efficiency and scalability of implementations

6. ...

LTL Knowledge Bases

timeline $(\mathbb{Z}, <)$

Basic Temporal Concepts

$$C \quad ::= \quad \bot \quad | \quad \top \quad | \quad A_i \quad | \quad \bigcirc_F C \quad | \quad \bigcirc_P C \quad | \quad \Box_F C \quad | \quad \Box_P C$$

where A_i are Atomic Concepts

TBox Axioms

$$C_1 \sqcap \cdots \sqcap C_k \sqsubseteq C_{n+1} \sqcup \cdots \sqcup C_{n+m}$$

bool any k and m

krom $k + m \leq 2$

horn $m \leq 1$

core $k + m \leq 2$ and $m \leq 1$

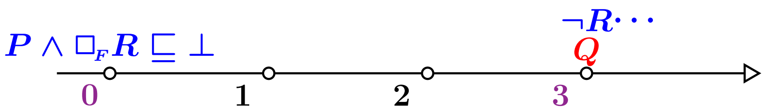
Fragments

LTL$_c^o$ $c \in \{$*bool*, *horn*, *krom*, *core*$\}$ and $o \in \{\Box, \bigcirc, \Box\bigcirc\}$

Expressivity of LTL^{o}_{c}

$P \sqsubseteq \Diamond_F Q$ can be expressed in $\mathit{LTL}^{\Box}_{krom}$ as $P \sqcap \Box_F R \sqsubseteq \bot, \quad \neg R \sqsubseteq Q$

for a fresh r



but **cannot be expressed in $\mathit{LTL}^{\Box\bigcirc}_{horn}$**

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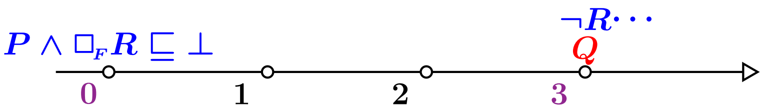

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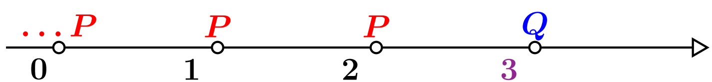
$\Diamond_F Q \sqsubseteq P$ can be expressed in $\mathit{LTL}^{\Box}_{core}$ as $Q \sqsubseteq \Box_P P$



Expressivity of LTL_c^o (cont.)

$A \sqsubseteq B \,\mathcal{U}\, C$ can be expressed in $\mathit{LTL}_{\mathit{bool}}^{\Box\bigcirc}$ using the unfolding $B \,\mathcal{U}\, C \equiv \bigcirc_F C \sqcup (\bigcirc_F B \sqcap \bigcirc_F (B \,\mathcal{U}\, C))$, which gives rise to four clauses:

$$A \sqsubseteq U, \quad U \sqsubseteq \bigcirc_F C \sqcup \bigcirc_F B, \quad U \sqsubseteq \bigcirc_F C \sqcup \bigcirc_F U, \quad A \sqsubseteq \Diamond_F C$$

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$B\,\mathcal{U}\,C \sqsubseteq A$ can be expressed in $LTL_{horn}^{\bigcirc}$ with the following clauses:

$$\bigcirc_F C \sqsubseteq U, \quad \bigcirc_F U \sqcap \bigcirc_F B \sqsubseteq U, \quad U \sqsubseteq A$$

LTL Knowledge Bases

LTL_c^o ontology $\mathcal{O}$ a set of LTL_c^o clauses $c \in \{$*bool*, *horn*, *krom*, *core*$\}$, $o \in \{\Box, \bigcirc, \Box\bigcirc\}$

Data instance $\mathcal{D}$ is a finite set of atoms of the form $A(\ell)$, $\ell \in \mathbb{Z}$

Active Domain of a data instance $\mathcal{D}$: $\mathbf{tem}(\mathcal{D}) = \{n \in \mathbb{Z} \mid \min \mathcal{D} \leq n \leq \max \mathcal{D}\}$

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Example

Ontology

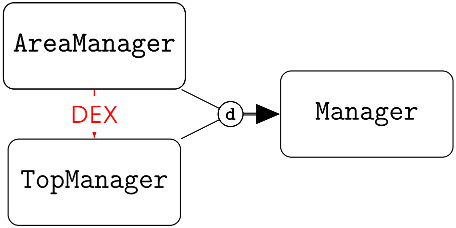
SevereSnow $\sqcap$ LowTemp $\sqcap$ StrongWind $\sqsubseteq$ BlizzardConditions
BlizzardConditions $\sqcap$ $\bigcirc_F$BlizzardConditions $\sqcap$ $\bigcirc_F\bigcirc_F$BlizzardConditions $\sqsubseteq$ Blizzard

Data instance

LowTemp(11am19/12/16)
SevereSnow(11am19/12/16)
StrongWind(11am19/12/16)

LTL in Ontologies

Consider the following **Ontology**



It can be captured by the following set of $LTL^{\Box}_{krom}$ clauses

$$\texttt{AreaManager} \sqsubseteq \texttt{Manager}$$

$$\texttt{TopManager} \sqsubseteq \texttt{Manager}$$

$$\texttt{AreaManager} \sqsubseteq \neg\texttt{TopManager}$$

$$\texttt{AreaManager} \sqsubseteq \Diamond_{F}\texttt{TopManager}$$

$\texttt{Manager} \sqsubseteq \texttt{TopManager} \sqcup \texttt{AreaManager}$ (Covering, $LTL^{\Box}_{bool}$)

Complexity Results for Satisfiability Problem of *LTL*

temp. ops. α	$\boxast, \Box_F, \Box_P, \bigcirc_F, \bigcirc_P$ $LTL_\alpha^{\Box\bigcirc}$	$\boxast, \Box_F, \Box_P$ $LTL_\alpha^{\Box}$	$\boxast, \bigcirc_F, \bigcirc_P$ $LTL_\alpha^{\bigcirc}$	$\boxast$ $LTL_\alpha^{\boxast}$
bool	PSPACE (SistlaClarke82)	NP (OnoNakamura80)	PSPACE	NP
horn	PSPACE (ChenLin93)	PTIME	PSPACE	PTIME
krom	NP	NP	NLOGSPACE	NLOGSPACE
core	NP	NLOGSPACE	NLOGSPACE	NLOGSPACE

Artale, Kontchakov, Ryzhikov, Zakharyaschev: The Complexity of Clausal Fragments of LTL. LPAR 2013.

Ontology-mediated queries in *LTL*

***LTL_c^o* ontology-mediated instance query** (OMIQ) is a pair $q = (\mathcal{O}, \varkappa)$

where $\mathcal{O}$ is an LTL_c^o ontology and

$$\varkappa \ ::= \ A \ \mid \ \neg\varkappa \ \mid \ \varkappa_1 \wedge \varkappa_2 \ \mid \ \varkappa_1 \vee \varkappa_2 \ \mid \ op_1\,\varkappa \ \mid \ \varkappa_1\, op_2\, \varkappa_2$$

$op_1 \in \{\bigcirc_F, \Diamond_F, \Box_F, \bigcirc_P, \Diamond_P, \Box_P\}$ and $op_2 \in \{\mathcal{U}, \mathcal{S}\}$

A is an Atomic Concept appearing in the ontology $\mathcal{O}$

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If $\varkappa$ is an atomic concept, $q = (\mathcal{O}, \varkappa)$ is an ***LTL_c^o* *ontology-mediated atomic query* (OMAQ).**

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A ***certain answer*** to q over a data instance $\mathcal{D}$, $\mathsf{ans}(q, \mathcal{D})$, is any $\ell \in \mathbf{tem}(\mathcal{D})$ such that, for every model $\mathfrak{M}$

$$\mathfrak{M} \models (\mathcal{O}, \mathcal{D}) \longrightarrow \mathfrak{M}, \ell \models \varkappa$$

FO-rewriting

An **FO$(<,+)$*-rewriting of*** q is an FO$(<,+)$-formula $q'(t)$ s.t.

$$\ell \in \mathbf{ans}(q,\mathcal{D}) \iff \mathfrak{S}_{\mathcal{D}} \models q'(\ell) \quad \text{for all } \mathcal{D},\ \ell \in \mathbf{tem}(\mathcal{D})$$

$$\mathfrak{S}_{\mathcal{D}} = (\mathcal{D}, <, \mathbf{tem}(\mathcal{D})), \text{ with } \mathfrak{S}_{\mathcal{D}} \models A(\ell) \quad \text{iff} \quad A(\ell) \in \mathcal{D}$$

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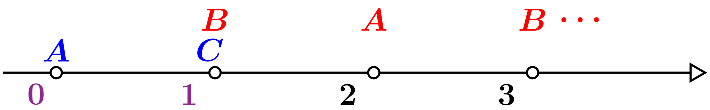
Evaluation of FO$(<,+)$-formulas is in LOGTIME-uniform **AC^0** for data complexity

Example – $LTL^{\bigcirc}_{core}$

Example 1 $\mathcal{D} = \{\mathrm{A}(0), \mathrm{C}(1)\}$, $\mathcal{O} = \{\, \bigcirc_{P} A \rightarrow B,\ \bigcirc_{P} B \rightarrow A \,\}$, $\varkappa = \bigcirc_{F} \bigcirc_{F} B$



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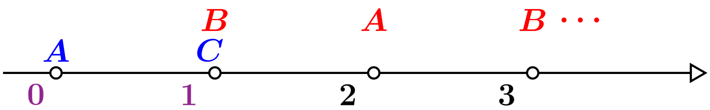

$\mathsf{ans}(q, \mathcal{D}) = \{1\}$ since $\min \mathcal{D} = 0$ and $\max \mathcal{D} = 1$

$\mathsf{ans}^{\mathbb{Z}}(q, \mathcal{D}) = \{2n + 1 \mid n \geq 0\}$

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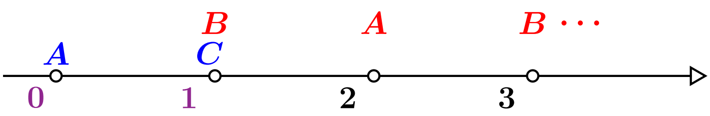

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FO$(<, +)$-rewriting

$$q'(t) = \exists s < t\, \exists n\, [(B(s) \land (t - s = 2n)) \lor (A(s) \land (t - s = 2n + 1))]$$

$t - s = 2n$ stands for $\exists k\, \big((k = n + n) \land (t = s + k)\big)$

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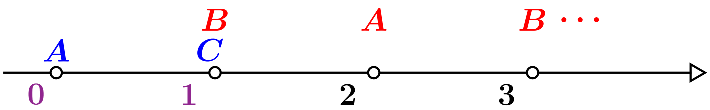

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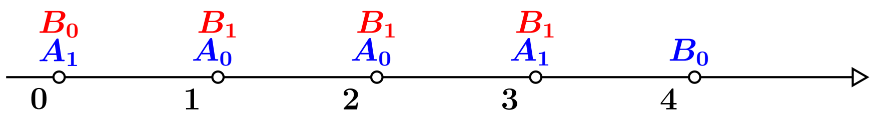
Note. The query is **not** FO$(<)$-rewritable since properties such as ***t is even*** are not definable by FO$(<)$-formulas (Libkin,04)

Example – $LTL^{\bigcirc}_{horn}$

Example 2 $\mathcal{O} = \{\bigcirc_{\!F} B_k \wedge A_0 \to B_k,\ \bigcirc_{\!F} B_k \wedge A_1 \to B_{1-k} \mid k = 0, 1\}$, $\varkappa = B_0$

for $e = (e_0, \dots, e_{n-1}) \in \{0,1\}^n$, $\mathcal{D}_e = \{\, \mathrm{A}_{\mathrm{e_i}}(\mathrm{i}) \mid 0 \leq i < n \,\} \cup \{\, \mathrm{B}_0(\mathrm{n}) \,\}$

$0 \in \mathsf{ans}(q, \mathcal{D}_e) \iff$ the number of 1s in e is even



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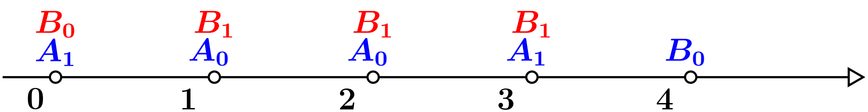

PARITY $\in$ $NC^1 \setminus AC^0$ (Furst,Saxe,Sipser,84) → **q is not FO-rewritable with any numeric predicates**

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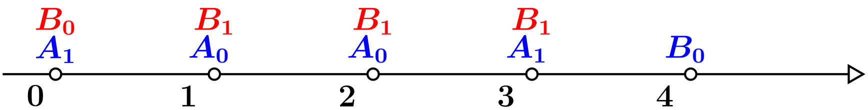

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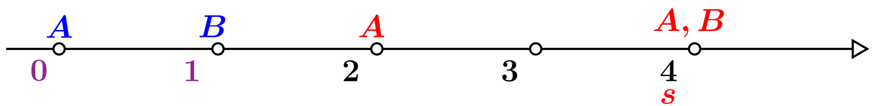
q is **FO(RPR)-rewritable**

Examples

Example 3 $\mathcal{O} = \{ A \to \bigcirc_F^2 A,\ B \to \bigcirc_F^3 B \}$, $\varkappa = \Diamond_F (A \wedge B)$

$$\exists s, u, v, n, m\, [(t < s) \wedge A(u) \wedge (s - u = 2n \geq 0) \wedge B(v) \wedge (s - v = 3m \geq 0)]$$

is a rewriting over $\mathbb{Z}$, but not over $\mathbf{tem}(\mathcal{D})$, indeed, let $\mathcal{D} = \{\mathrm{A}(0), \mathrm{B}(1)\}$



then $s = 4$ is **outside the active domain** $\mathbf{tem}(\mathcal{D}) = \{0, 1\}$ of $\mathcal{D}$.

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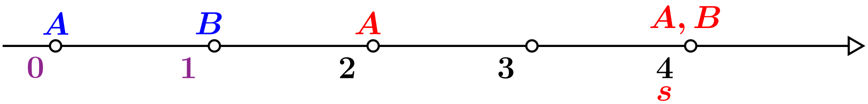

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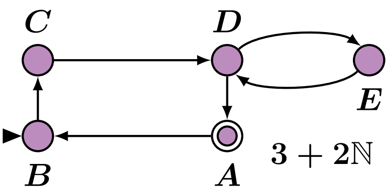
The following is both an FO($<$)- and FO$^{\mathbb{Z}}$($<$)-rewriting of q:

$$\exists u, v\, \big[A(u) \wedge B(v)\big]$$

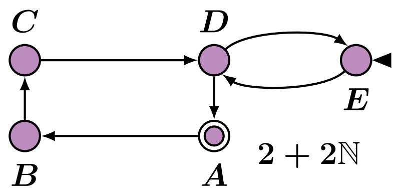
Automata for proving rewritability of OMAQ – $LTL^{\bigcirc}_{krom}$

Example – $LTL^{\bigcirc}_{core}$ $q = (\mathcal{O}, A)$ with (using **unary automata**)

$$\mathcal{O} = \{\, A \to \bigcirc B,\ \ B \to \bigcirc C,\ \ C \to \bigcirc D,\ \ D \to \bigcirc A,\ \ D \to \bigcirc E,\ \ E \to \bigcirc D \,\}$$



$$\exists s\,\big(B(s)\ \wedge\ (t - s \in 3 + 2\mathbb{N})\big)$$

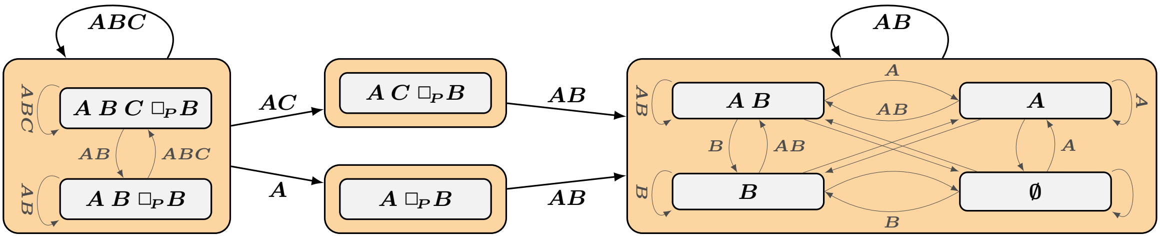


$$\exists s\,\big(E(s)\ \wedge\ (t - s \in 2 + 2\mathbb{N})\big)$$

Automata for proving rewritability of OMAQ – $LTL^{\Box}_{bool}$

Example – $LTL^{\Box}_{bool}$ $q = (\mathcal{O}, A)$ with $\mathcal{O} = \{ C \sqsubseteq \Box_P B,\ \Box_P B \sqsubseteq A \}$

(using partially-ordered automata)



Data Complexities of *LTL* OMQ's

<table>
<tr><th rowspan="2">c</th><th colspan="3">OMAQs (Atomic Queries)</th><th colspan="3">OMPIQs / positive MFO(<) queries</th></tr>
<tr><th>$LTL_c^{\Box}$</th><th>$LTL_c^{\bigcirc}$</th><th>$LTL_c^{\Box\bigcirc}$</th><th>$LTL_c^{\Box}$</th><th>$LTL_c^{\bigcirc}$</th><th>$LTL_c^{\Box\bigcirc}$</th></tr>
<tr><td>bool</td><td rowspan="4">FO(<)</td><td colspan="2" rowspan="2">MSO(<), FO(RPR)</td><td>MSO(<)</td><td colspan="2" rowspan="3">MSO(<), FO(RPR)</td></tr>
<tr><td>horn</td><td>FO(<)</td></tr>
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</table>

$LTL_{bool}^{\Box\bigcirc}$ OMAQs are MSO(<)-rewritable →

OMAQ answering is in $\mathbf{NC}^1$ for data complexity

Answering $LTL_{horn}^{\bigcirc}$ OMAQs is $\mathbf{NC}^1$-hard for data complexity

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<table>
<tr><th rowspan="2">c</th><th colspan="3">OMAQs (Atomic Queries)</th><th colspan="3">OMPIQs / positive MFO($<$) queries</th></tr>
<tr><th>$LTL_c^{\Box}$</th><th>$LTL_c^{\bigcirc}$</th><th>$LTL_c^{\Box\bigcirc}$</th><th>$LTL_c^{\Box}$</th><th>$LTL_c^{\bigcirc}$</th><th>$LTL_c^{\Box\bigcirc}$</th></tr>
<tr><td>*bool*</td><td rowspan="4">FO($<$)</td><td colspan="2" rowspan="2">MSO($<$), FO(RPR)</td><td>MSO($<$)</td><td colspan="2" rowspan="3">MSO($<$), FO(RPR)</td></tr>
<tr><td>*horn*</td><td>FO($<$)</td></tr>
<tr><td>*krom*</td><td colspan="2" rowspan="2">FO($<$,+)</td><td>MSO($<$)</td></tr>
<tr><td>*core*</td><td>FO($<$)</td><td colspan="2">FO($<$,+)</td></tr>
</table>

$LTL_{bool}^{\Box\bigcirc}$ OMAQs are MSO($<$)-rewritable →

OMAQ answering is in **NC^1** for data complexity

Answering $LTL_{horn}^{\bigcirc}$ OMAQs is **NC^1**-hard for data complexity

MFO($<$): monadic first-order logic with a built-in linear order

$$\psi(t, t') = \exists x \, \big((t < x < t') \land \texttt{Revise}(x)\big) \land \texttt{Submission}(t) \land \texttt{Accept}(t').$$

Answering positive MFO queries has the same data complexity as OMPIQ queries

Conclusions and Future Work

- Investigation of FO-rewritability for temporal ontology-mediated queries based on linear temporal logic *LTL*.
- Classification of the OMQs by the shape of their ontology axioms (core, horn, krom or bool) and by the temporal operators in the ontology axioms.
- **Data Complexity**: Identification of **FO**$(<)$, **FO**$(<,+)$, **FO**$(\mathbf{RPR})$ rewriting results for certain classes of OMQ's.
- Generalise FO rewritings of OMQs to **(2-sorted) CQs**, **positive MFO**$(<)$.

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- Extend the result to temporal extensions of *DL-Lite*: we are investigating $\textit{DL-Lite}_{core}$ with $\textit{LTL}^{\Box}_{core}$, and $\textit{DL-Lite}_{core}$ with $\textit{LTL}^{\Box\bigcirc}_{core}$.
- Investigate other form of temporal languages (Intervals, Metric, etc.)

Thank you!