

News on Temporal Conjunctive Queries

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Ontology-Based Data Access

Use Case: Finding Participants for Clinical Trial

Example¹

- Previously infected with VZV or previously vaccinated with VZV vaccine
- No Allergy to VZV vaccine

¹<https://clinicaltrials.gov/ct2/show/NCT01953900>

Ontology-Based Data Access

Patients infected with VZV?

PID	Name
1	Ann
2	Bob
3	Chris

Patient

PID	Finding	Date
1	Chickenpox	08/2017
2	VZV-Infection	01/2010
3	VZV-Infection	11/2011

Finding

PID	AllergyTest	Date
1	neg	07/2017
2	pos	09/2017
3	neg	06/1970

Test

Ontology-Based Data Access

Patients infected with VZV?

```
SELECT ID FROM Pat
```

```
WHERE Pat.PID=Find.PID & Find.TYPE=VZVInfect
```

PID	Name
1	Ann
2	Bob
3	Chris

Patient

PID	Finding	Date
1	Chickenpox	08/2017
2	VZV-Infection	01/2010
3	VZV-Infection	11/2011

Finding

PID	AllergyTest	Date
1	neg	07/2017
2	pos	09/2017
3	neg	06/1970

Test

Ontology-Based Data Access

Patients infected with VZV?

Patient

	VZV	Virus
	Chickenpox	VZVInfection
HasFinding	Allergy	\exists AllergyTo

PID	Name
1	Ann
2	Bob
3	Chris

Patient

PID	Finding	Date
1	Chickenpox	08/2017
2	VZV-Infection	01/2010
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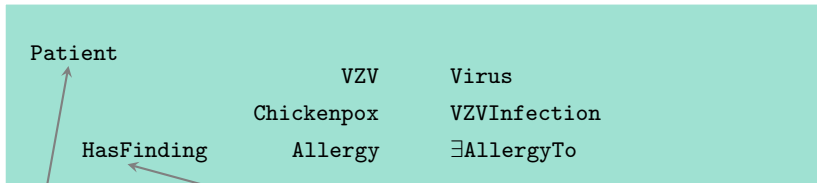
Finding

PID	AllergyTest	Date
1	neg	07/2017
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Test

Ontology-Based Data Access

Patients infected with VZV?



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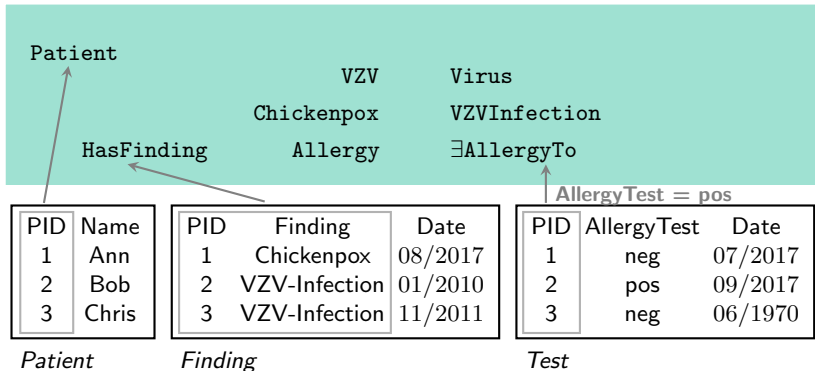
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1	neg	07/2017
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Test

Ontology-Based Data Access

Patients infected with VZV?



Ontology-Based Data Access

Patients infected with VZV?

Patient

VZV

Virus

Chickenpox

VZVInfection

HasFinding

Allergy

\exists AllergyTo

Patient(ann)

$\neg \exists$ AllergyTo(ann)

HasFinding(ann, f1)

Chickenpox(f1)

Patient(bob)

Ontology-Based Data Access

Patients infected with VZV?

Answer: x

$\text{Patient}(x) \wedge \exists y. \text{HasFinding}(x, y) \wedge \text{VZVInfection}(y)$

Patient

VZV

Virus

Chickenpox

VZVInfection

HasFinding

Allergy

\exists AllergyTo

$\text{Patient}(\text{ann})$

$\neg \exists \text{AllergyTo}(\text{ann})$

$\text{HasFinding}(\text{ann}, \text{f1})$

$\text{Chickenpox}(\text{f1})$

$\text{Patient}(\text{bob})$

Ontology-Based Data Access

Patients infected with VZV?

Answer: x

$\text{Patient}(x) \wedge \exists y. \text{HasFinding}(x, y) \wedge \text{VZVInfection}(y)$

Patient

$\forall x. \text{VZV}(x) \rightarrow \text{Virus}(x)$

$\forall x. \text{Chickenpox}(x) \rightarrow \text{VZVInfection}(x)$

HasFinding

Allergy

$\exists \text{AllergyTo}$

Patient(ann)

$\neg \exists \text{AllergyTo}(\text{ann})$

HasFinding(ann, f1)

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Ontology-Based Data Access

Patients infected with VZV?

Answer: x

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Patient

$\forall x. \text{VZV}(x) \rightarrow \text{Virus}(x)$

$\forall x. \text{Chickenpox}(x) \rightarrow \text{VZVInfection}(x)$

$\forall xy. \text{HasFinding}(x, y) \wedge \text{Allergy}(y) \rightarrow \exists \text{AllergyTo}(x)$

$\text{Patient}(\text{ann})$

$\neg \exists \text{AllergyTo}(\text{ann})$

$\text{HasFinding}(\text{ann}, \text{f1})$

$\text{Chickenpox}(\text{f1})$

$\text{Patient}(\text{bob})$

Ontology-Based Data Access

Patients infected with VZV?

Answer: $x = \text{ann}$

$\text{Patient}(x) \wedge \exists y. \text{HasFinding}(x, y) \wedge \text{VZVInfection}(y)$

Patient

$\forall x. \text{VZV}(x) \rightarrow \text{Virus}(x)$

$\forall x. \text{Chickenpox}(x) \rightarrow \text{VZVInfection}(x)$

$\forall xy. \text{HasFinding}(x, y) \wedge \text{Allergy}(y) \rightarrow \exists \text{AllergyTo}(x)$

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$\neg \exists \text{AllergyTo}(\text{ann})$

$\text{HasFinding}(\text{ann}, \text{f1})$

$\text{Chickenpox}(\text{f1})$

$\text{Patient}(\text{bob})$

Ontology-Based Data Access: Temporal Queries

Patients **infected with VZV previously**, not allergic to VZV vaccine (now)?

Patient

$$\forall x.VZV(x) \rightarrow Virus(x)$$
$$\forall x.Chickenpox(x) \rightarrow VZVInfection(x)$$
$$\forall xy.HasFinding(x, y) \wedge Allergy(y) \rightarrow \exists AllergyTo(x)$$

Patient(ann)

$\neg \exists AllergyTo(ann)$

HasFinding(ann, f1)

Chickenpox(f1)

Patient(bob)

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07/17

Patient(ann)

$\neg \exists AllergyTo(ann)$

08/17

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Ontology-Based Data Access: Temporal Queries

Patients **infected with VZV previously**, not allergic to VZV vaccine (now)?

$\text{Patient}(x) \wedge \diamond_P \exists y. \text{HasFinding}(x, y) \wedge \text{VZVInfection}(x)$

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07/17

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08/17

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08/17

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Ontology-Based Data Access: Temporal Queries with Rigid Symbols

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Patient

$$\forall x. \text{VZV}(x) \rightarrow \text{Virus}(x)$$
$$\forall x. \text{Chickenpox}(x) \rightarrow \text{VZVInfection}(x)$$
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07/17

Patient(ann)

$\neg \exists \text{AllergyTo}$ (ann)

08/17

Patient(ann)

HasFinding(ann, f1)

Chickenpox(f1)

09/17

Patient(ann)

$\neg \exists \text{AllergyTo}$ (ann)

Patient(bob)

Ontology-Based Data Access: Temporal Queries

- **Temporal conjunctive queries:** conjunctive queries (CQs) + LTL

Ontology-Based Data Access: Temporal Queries

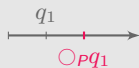
- **Temporal conjunctive queries:** conjunctive queries (CQs) + LTL

TCQ $q_1, q_2 := \text{CQ } q \mid \neg q_1 \text{ (not)} \mid q_1 \wedge q_2 \text{ (and)} \mid q_1 \vee q_2 \text{ (or)} \mid$

Ontology-Based Data Access: Temporal Queries

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TCQ $q_1, q_2 :=$ CQ q | $\neg q_1$ (not) | $q_1 \wedge q_2$ (and) | $q_1 \vee q_2$ (or) |
 $\circ_F q_1$ (next) | $\circ_P q_1$ (previous) |



Ontology-Based Data Access: Temporal Queries

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$\rightarrow \diamond_P q_2 := \text{true} \mathcal{S} q_2$ (some time in the past)

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$\rightarrow \diamond_P q_2 := \text{true } \mathcal{S} q_2$ (some time in the past)

Semantics: sequences of DL interpretations $\mathfrak{I} = (\Delta, \mathcal{I}_i)_{i \in \mathbb{N}}$

Example

$\mathfrak{I}, 3 \models \circ_P \text{Patient}(\text{ann})$ iff $\mathcal{I}_2 \models \text{Patient}(\text{ann})$

Ontology-Based Data Access: Temporal Queries

- **Temporal conjunctive queries:** conjunctive queries (CQs) + LTL
- **Ontology:** lightweight description logics (DLs)
- **Temporal data:** sequence of fact bases

Ontology-Based Data Access: Temporal Queries

- **Temporal conjunctive queries:** conjunctive queries (CQs) + LTL
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I

Problem: Temporal query entailment

Results: Computational complexity

Application: Choose languages according
to available resources
(time and memory)

Ontology-Based Data Access: Temporal Queries

- **Temporal conjunctive queries:** conjunctive queries (CQs) + LTL
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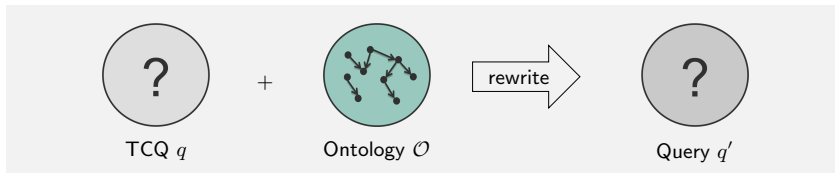
II

Temporal query answering
Rewritability
Hints for implementation (use existing tools)

Ontology-Based Data Access: Temporal Queries

- **Temporal conjunctive queries:** conjunctive queries (CQs) + LTL
- **Ontology:** lightweight description logics (DLs)
- **Temporal data:** sequence of fact bases

	I	II
Problem:	Temporal query entailment	Temporal query answering
Results:	Computational complexity	Rewritability
Application:	Choose languages according to available resources (time and memory)	Hints for implementation (use existing tools)



Rewritability: Answers to q w.r.t. $\langle O, (\mathcal{D})_{0 \leq i \leq n} \rangle =$ Answers to q' over $(\mathcal{D})_{0 \leq i \leq n}$

Ontology-Based Data Access: Temporal Queries

I Temporal Query Entailment

Given: Boolean TCQ q , $\langle \mathcal{O}, (\mathcal{D}_i)_{0 \leq i \leq n} \rangle$

Problem: $\langle \mathcal{O}, (\mathcal{D}_i)_{0 \leq i \leq n} \rangle, n \models q$

Ontology-Based Data Access: Temporal Queries

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Rigid Symbols	Combined Complexity			Data Complexity		
	none	classes	all	none	classes	all
$DL\text{-Lite}_{[core horn]}^{\mathcal{H}}$	$\geq \text{PSPACE}$?	?	?	?	?
\mathcal{EL}	$\geq \text{PSPACE}$?	?	$\geq \text{P}$?	?
$DL\text{-Lite}_{[krom bool]}$	$\geq \text{PSPACE}$?	?	$\geq \text{co-NP}$?	?
$DL\text{-Lite}_{[krom bool]}^{\mathcal{H}}$	$\geq 2\text{-ExpTime}$?	?	$\geq \text{co-NP}$?	?
\mathcal{ALCHQ}^1	ExpTime	co-NEPTime	2-ExpTime	co-NP	co-NP	$\leq \text{ExpTime}$

¹[Baader et al., JWS'15]

Ontology-Based Data Access: Temporal Queries

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Rigid Symbols	Combined Complexity			Data Complexity		
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$DL-Lite_{[core horn]}^{\mathcal{H}}$	$\geq PSPACE$?	?	?	?	?
\mathcal{EL}	$\geq PSPACE$?	?	$\geq P$?	?
$DL-Lite_{[krom bool]}$	$\geq PSPACE$?	PSpace?	$\geq CO-NP$?	?
$DL-Lite_{[krom bool]}^{\mathcal{H}}$	$\geq 2-ExpTime$?	?	$\geq CO-NP$?	?
\mathcal{ALCHQ}^1	ExpTime	CO-NExpTime	2-ExpTime	CO-NP	CO-NP	$\leq ExpTime$

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Ontology-Based Data Access: Temporal Queries

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Rigid Symbols	Combined Complexity			Data Complexity		
	none	classes	all	none	classes	all
$DL-Lite_{[core horn]}^{\mathcal{H}}$	$\geq PSPACE$?	?	?	?	FO-rewritable?
\mathcal{EL}	$\geq PSPACE$?	?	$\geq P$?	?
$DL-Lite_{[krom bool]}$	$\geq PSPACE$?	PSPACE?	$\geq CO-NP$?	?
$DL-Lite_{[krom bool]}^{\mathcal{H}}$	$\geq 2-EXPTIME$?	?	$\geq CO-NP$?	?
\mathcal{ALCHQ}^1	EXPTIME	CO-NEXPTIME	2-EXPTIME	CO-NP	CO-NP	$\leq EXPTIME$

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Ontology-Based Data Access: Temporal Queries

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Rigid Symbols	Combined Complexity			Data Complexity		
	none	classes	all	none	classes	all
$DL-Lite_{[core horn]}^{\mathcal{H}}$	$\geq PSPACE$?	?	?	?	FO-rewritable?
\mathcal{EL}	$\geq PSPACE$?	?	$\geq P$?	Tractable?
$DL-Lite_{[krom bool]}$	$\geq PSPACE$?	PSPACE?	$\geq CO-NP$?	?
$DL-Lite_{[krom bool]}^{\mathcal{H}}$	$\geq 2-ExpTime$?	?	$\geq CO-NP$?	?
\mathcal{ALCHQ}^1	ExpTime	CO-NExpTime	2-ExpTime	CO-NP	CO-NP	$\leq ExpTime$

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\mathcal{EL}	$\geq \text{PSPACE}$?	?	$\geq \text{P}$?	Tractable?
$DL\text{-Lite}_{[krom bool]}$	$\geq \text{PSPACE}$?	PSPACE?	$\geq \text{co-NP}$?	?
$DL\text{-Lite}_{[krom bool]}^{\mathcal{H}}$	$\geq 2\text{-ExpTIME}$?	?	$\geq \text{co-NP}$?	? co-NP?
\mathcal{ALCHQ}^1	ExpTIME	co-NEPTime	2-ExpTIME	co-NP	co-NP	$\leq \text{ExpTIME}$

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	none	classes	all	none	classes	all
$DL-Lite_{[core horn]}^{\mathcal{H}}$	PSPACE	PSPACE	PSPACE	?	?	FO-rewritable?
\mathcal{EL}	PSPACE	PSPACE	?	$\geq P$?	Tractable?
$DL-Lite_{[krom bool]}$	$\geq PSPACE$?	PSPACE?	$\geq CO-NP$?	?
$DL-Lite_{[krom bool]}^{\mathcal{H}}$	$\geq 2-ExpTime$?	?	$\geq CO-NP$?	? co-NP?
\mathcal{ALCHQ}^1	ExpTime	CO-NEPTime	2-ExpTime	CO-NP	CO-NP	$\leq ExpTime$

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\mathcal{EL}	PSPACE	PSPACE	CO-NEXPTIME	$\geq P$?	Tractable?
$DL-Lite_{[krom bool]}$	EXPTIME	CO-NEXPTIME	2-EXPTIME	$\geq \text{co-NP}$?	?
$DL-Lite_{[krom bool]}^{\mathcal{H}}$	2-EXPTIME	2-EXPTIME	2-EXPTIME	$\geq \text{co-NP}$?	? co-NP?
\mathcal{ALCHQ}^1	EXPTIME	CO-NEXPTIME	2-EXPTIME	CO-NP	CO-NP	$\leq \text{ExpTime}$

- Strong impact of rigid symbols

¹[Baader et al., JWS'15]

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$DL-Lite_{[core horn]}^{\mathcal{H}}$	PSPACE	PSPACE	PSPACE	NC ¹	NC ¹	NC ¹
\mathcal{EL}	PSPACE	PSPACE	CO-NEXPTIME	$\geq P$?	Tractable?
$DL-Lite_{[krom bool]}$	EXPTIME	CO-NEXPTIME	2-EXPTIME	$\geq \text{co-NP}$?	?
$DL-Lite_{[krom bool]}^{\mathcal{H}}$	2-EXPTIME	2-EXPTIME	2-EXPTIME	$\geq \text{co-NP}$?	? co-NP?
$ALCHQ^1$	EXPTIME	CO-NEXPTIME	2-EXPTIME	CO-NP	CO-NP	$\leq \text{EXPTIME}$

- Strong impact of rigid symbols
- Horn $DL-Lite$: rigid symbols not critical, but no FO-rewritability
→ NC¹: efficient parallel algorithms exist

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	none	classes	all	none	classes	all
$DL-Lite_{[core horn]}^{\mathcal{H}}$	PSPACE	PSPACE	PSPACE	NC ¹	NC ¹	NC ¹
\mathcal{EL}	PSPACE	PSPACE	CO-NEXPTIME	P	CO-NP	CO-NP
$DL-Lite_{[krom bool]}$	EXPTIME	CO-NEXPTIME	2-EXPTIME	\geq CO-NP	?	?
$DL-Lite_{[krom bool]}^{\mathcal{H}}$	2-EXPTIME	2-EXPTIME	2-EXPTIME	\geq CO-NP	?	? co-NP?
\mathcal{ALCHQ}^1	EXPTIME	CO-NEXPTIME	2-EXPTIME	CO-NP	CO-NP	\leq EXPTIME

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Ontology-Based Data Access: Temporal Queries

I Temporal Query Entailment

Given: Boolean TCQ q , $\langle \mathcal{O}, (\mathcal{D}_i)_{0 \leq i \leq n} \rangle$

Problem: $\langle \mathcal{O}, (\mathcal{D}_i)_{0 \leq i \leq n} \rangle, n \models q$

Rigid Symbols	Combined Complexity			Data Complexity		
	none	classes	all	none	classes	all
$DL-Lite_{[core horn]}^{\mathcal{H}}$	PSPACE	PSPACE	PSPACE	NC ¹	NC ¹	NC ¹
\mathcal{EL}	PSPACE	PSPACE	CO-NEXPTIME	P	CO-NP	CO-NP
$DL-Lite_{[krom bool]}$	EXPTIME	CO-NEXPTIME	2-EXPTIME	CO-NP	CO-NP	CO-NP
$DL-Lite_{[krom bool]}^{\mathcal{H}}$	2-EXPTIME	2-EXPTIME	2-EXPTIME	CO-NP	CO-NP	CO-NP
$ALCHQ^1$	EXPTIME	CO-NEXPTIME	2-EXPTIME	CO-NP	CO-NP	\leq EXPTIME

- Strong impact of rigid symbols
- Horn $DL-Lite$: rigid symbols not critical, but no FO-rewritability
→ NC¹: efficient parallel algorithms exist
- Other $DL-Lite$ variants comparable to very expressive DLs
- Data complexity: temporal features for free!

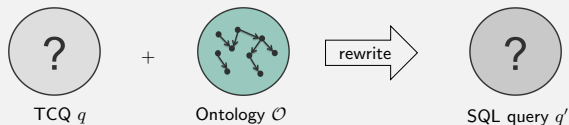
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Ontology-Based Data Access: Temporal Queries

II Temporal Query Answering

Given: TCQs, $DL-Lite_{horn}$, SQL

Problem: Is TCQ answering w.r.t. ontologies in $DL-Lite_{horn}$ rewritable to SQL?

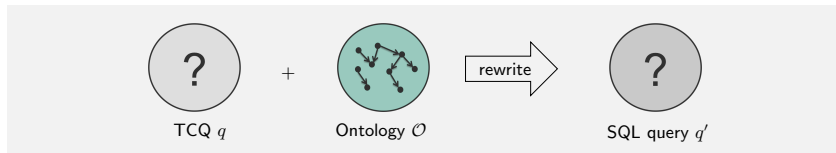


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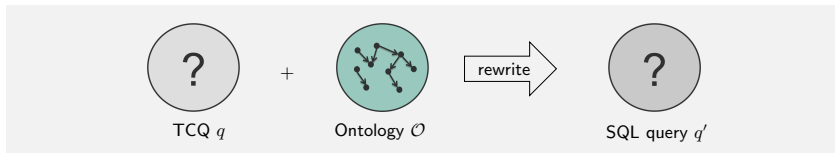
Solution: Holds for positive TCQs (conjunctive queries + LTL w/o negation)

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Generic rewritability result

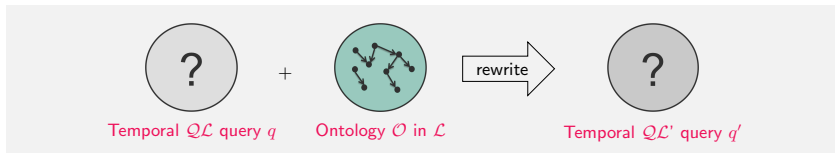
For positive temporal QL queries (QL queries + LTL w/o negation) and lightweight logics \mathcal{L} if they satisfy certain conditions.

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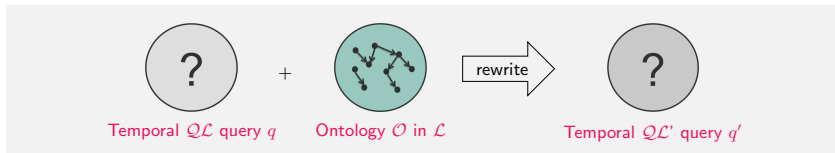
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For positive temporal QL queries (QL queries + LTL w/o negation) and lightweight logics \mathcal{L} if they satisfy certain conditions.

Many formalisms satisfy our conditions!

Ontology-Based Data Access: Temporal Queries

II Temporal Query Answering

\mathcal{L}	\mathcal{QL}	\mathcal{QL}'
\mathcal{EL}^{++}	subs.	subs.
$DL\text{-Lite}_{\mathcal{R}}$	CQ	UCQ
$\mathcal{ELH}_{\perp}^{dr}$	CQ	FO ₌
$DL\text{-Lite}_{horn}^{\mathcal{N}}$	CQ	FO ₌
$DL\text{-Lite}_{\mathcal{R}}$	UCQ	PEQ
$DL\text{-Lite}$	CQ	UCQ
\mathcal{ELHI}^{\neg}	CQ	Datalog
Horn- $\mathcal{ALCHI}Q$	CQ	UCQ
\mathcal{LDL}^+	IQ	IQ
$SROEL(\sqcap, \times)$	IQ	IQ
Datalog [±] family	CQ	UCQ

Summary & Outlook

- Temporal query answering w.r.t. ontologies in lightweight logics
- Focus on description logics
- Complexity and rewritability results [Borgwardt et al., JWS'15, IJCAI'15, GCAI'15], [T., WSP'17]
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Treatment $\sqcap \circ_F ((\neg \text{Treatment}) \mathcal{U}_{[45,180]} \text{Reaction})$

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Thank you!

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