TECHNISCHE UNIVERSITÄT DRESDEN

Stefan Borgwardt

The Complexity Landscape of Temporal Conjunctive Queries

Workshop on High-Level Declarative Stream Processing // Berlin, 25.09.2018

Declarative Stream Processing

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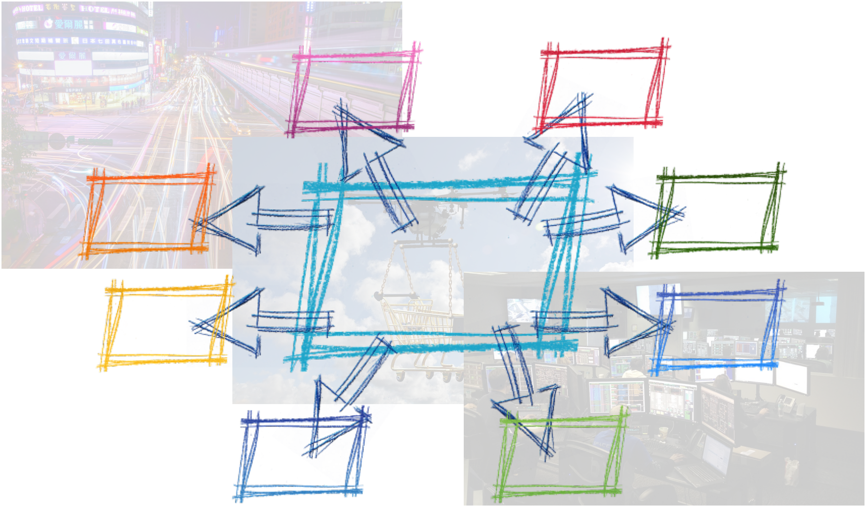
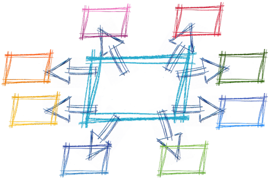


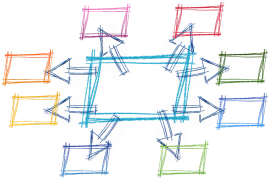
High-Level Models



Abstract entities & relations

High-Level Models

Discretized input signals



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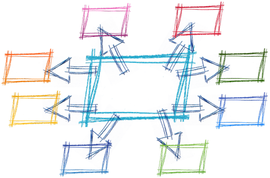

Abstract entities & relations

Ontology

In This Talk

- Description Logic / OWL Ontologies

SNOMED International

Leading healthcare terminology, worldwide

protégé

Dublin Core Metadata Initiative®

Making it easier to find information.

In This Talk

- Description Logic / OWL Ontologies

- Temporal Logic Queries

In This Talk

- Description Logic / OWL Ontologies
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- Computational Complexity

$$\mathrm{AC}^0 \subseteq \mathrm{NC}^1 \subseteq \mathrm{P} \subseteq \mathrm{NP} \subseteq \textsc{PSpace} \subseteq \textsc{Exp} \subseteq \textsc{NExp} \subseteq \textsc{2Exp}$$

Description Logic Ontologies

Concept names	**Drone**, **Component**, **Sensor**
Role names	**hasModel**, **isPartOf**
Individual names	**drone-AB100**, **myDrone**

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Assertions	$\mathsf{drone\text{-}AB100} : \mathsf{DeliveryDrone}$, $(\mathsf{drone\text{-}AB100}, \mathsf{ErnstReuterPlatz}) : \mathsf{hasLocation}$

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Concept inclusions	$\mathsf{DeliveryDrone} \sqsubseteq \mathsf{Drone}$, $\mathsf{InfraredSensor} \sqsubseteq \exists \mathsf{measures}.\mathsf{Heat}$

Description Logic Ontologies

Concept names — Drone, Component, Sensor

Role names — hasModel, isPart

Individual names — drone-AB100, myDrone

Concepts — ne ⊓ sSenso fraredSensor

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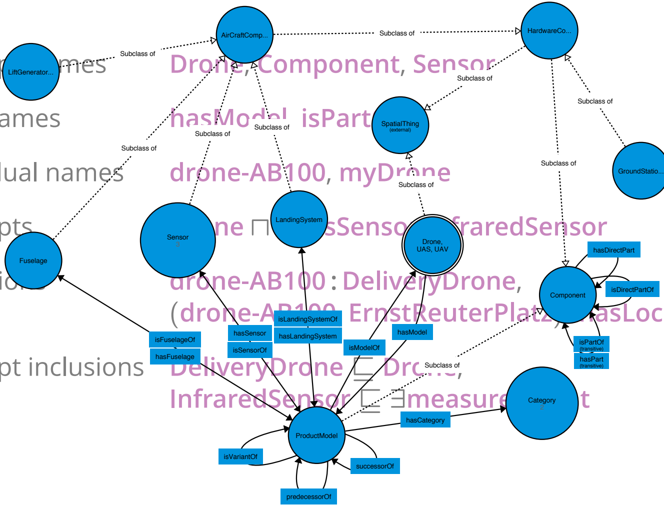
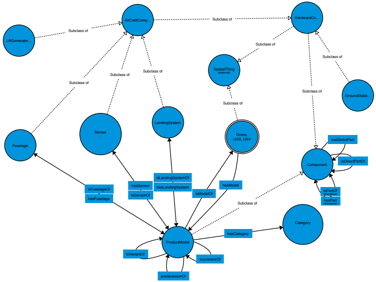


Temporal Ontologies

Ontology $\mathcal{O}$



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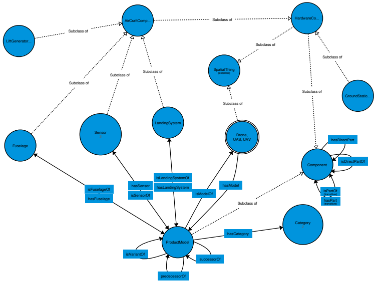

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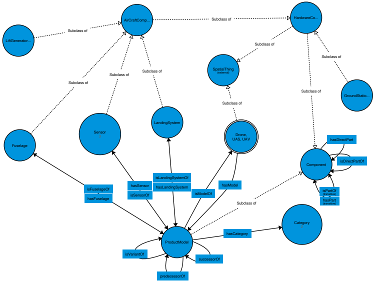

Query Q

Assertions $\mathcal{A}_0$ $\mathcal{A}_1$ $\ldots$ $\mathcal{A}_n$

Temporal Conjunctive Queries (TCQs)

Conjunctive queries, a subclass of SQL:

$$q(d)\colon \exists s,p.\ \mathsf{Drone}(d) \land \mathsf{hasSensor}(d,s) \land \mathsf{measures}(s,p) \land \mathsf{HighAcceleration}(p)$$

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...combined via linear temporal operators (plus $\land$, $\lor$, $\neg$):

$$Q(d):\ \boxed{\mathsf{Drone}(d)} \land \boxed{\exists e.\ \mathsf{hasLocation}(d,e) \land \mathsf{ErnstReuterPlatz}(e)} \land \\ \Diamond^{-} \boxed{\exists f.\ \mathsf{hasLocation}(d,f) \land \mathsf{Hauptbahnhof}(f)}$$

(Baader, Borgwardt, and Lippmann 2013; Baader, Ghilardi, and Lutz 2012)

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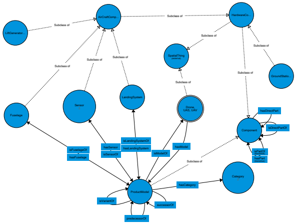
More expressive and expensive

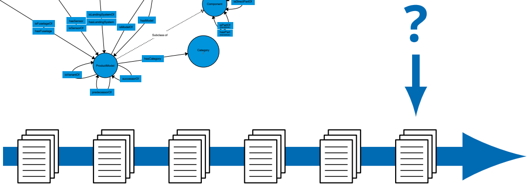
Undecidable in combination with rigid roles

No tools to develop temporal DL ontologies exist

(Gabbay, Kurucz, Wolter, and Zakharyaschev 2003)

Answering TCQs





Does the query Q follow from the ontology $\mathcal{O}$ and observations $\mathcal{A}_0, \ldots, \mathcal{A}_n$, taking the rigid names into account?

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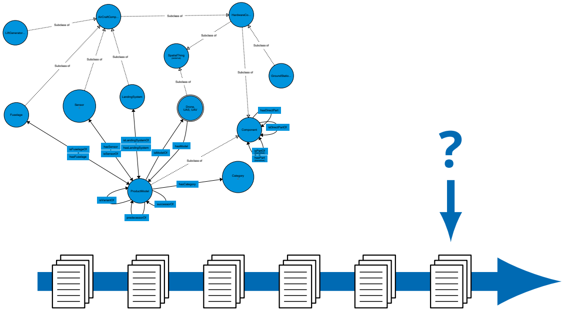

Does the query Q follow from the ontology $\mathcal{O}$ and observations $\mathcal{A}_0, \ldots, \mathcal{A}_n$, taking the rigid names into account?

Do Q, $\mathcal{O}$, and $\mathcal{A}_0, \ldots, \mathcal{A}_n$ have a common model, respecting the rigid names?

Complexity Landscape

Description logic	Data complexity 0	1	2	3	Combined complexity 0	1	2	3
DL-Lite	AC^0	NC^1			NP	PSPACE		

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Propositional Abstraction

- To decide satisfiability of Q over $\mathcal{O}$ and $\mathcal{A}_0, \ldots, \mathcal{A}_n$, replace the inner CQs $q_1, \ldots, q_m$ by propositional variables $p_1, \ldots, p_m$.

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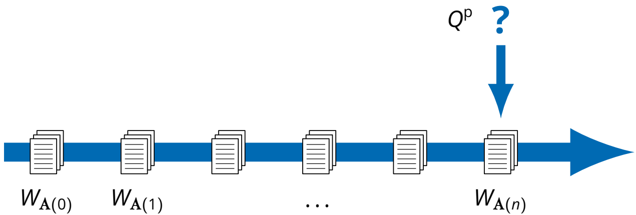
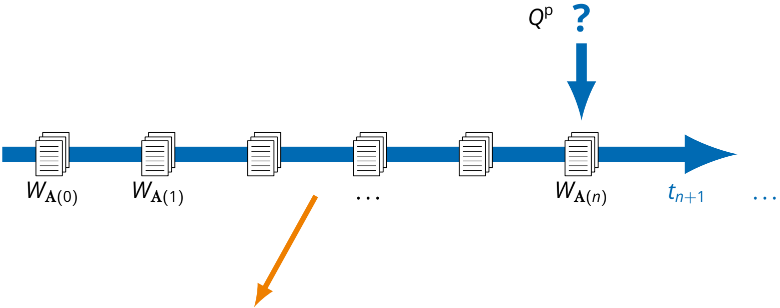
- mapping $\mathbf{A} \colon \{0, \ldots, n\} \to \{1, \ldots, k\}$



Main Approach



T-satisfiability

LTL model $t_0, t_1, \dots$ of Q^{p} with

- $t_i = W_{\mathbf{A}(i)}$ for $0 \leq i \leq n$
- $t_i \in \mathbf{W}$ for $i > n$

P / PSPACE

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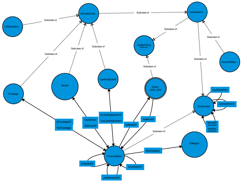

$$Q_i: \bigwedge_{p_j \in W_i} q_j \wedge \bigwedge_{p_j \notin W_i} \neg q_j$$

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R-satisfiability

Models of

- $Q_{\mathbf{A}(i)}, \mathcal{A}_i$ and $\mathcal{O}$ for $0 \leq i \leq n$
- Q_i and $\mathcal{O}$ for $1 \leq i \leq k$

that respect the rigid names.

R-satisfiability in Case 1 (No Rigid Names)

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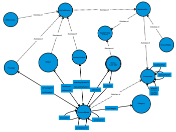

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independent atemporal satisfiability checks
$\rightsquigarrow$ "maximal" set $\mathbf{W}$, mapping $\mathbf{A}$

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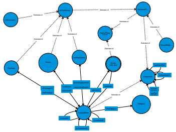

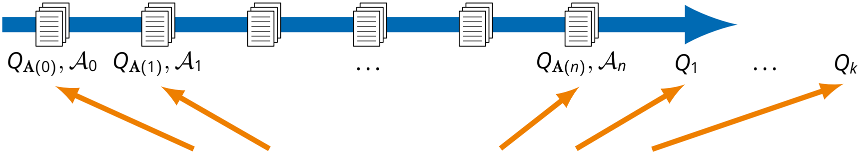

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(Baader, Borgwardt, and Lippmann 2013; Borgwardt and Thost 2015b)

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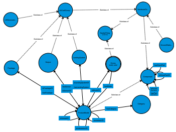

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integrate satisfiability check by renaming the flexible names:

$$Q^{(0)}_{\mathbf{A}(0)}, \mathcal{A}^{(0)}_0, \ldots, Q^{(n)}_{\mathbf{A}(n)}, \mathcal{A}^{(n)}_n, Q^{(n+1)}_1, \ldots, Q^{(n+k)}_k, \mathcal{O}^{(0)}, \ldots, \mathcal{O}^{(n+k)}$$

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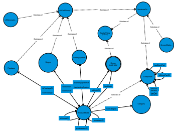

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(Borgwardt and Thost 2015a)

DL-Lite

AC^0 | NC^1 | NP | **PSPACE**

- Guess additional information $\mathbf{P}$
- Do not construct $\mathbf{W}$ and $\mathbf{A}$ explicitly
- Combine T-satisfiability and R-satisfiability checks

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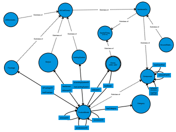

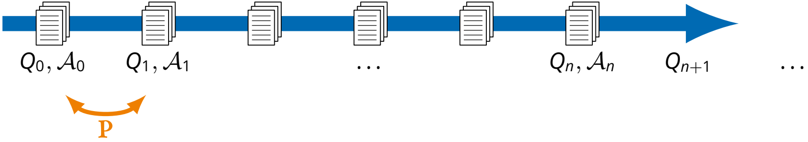

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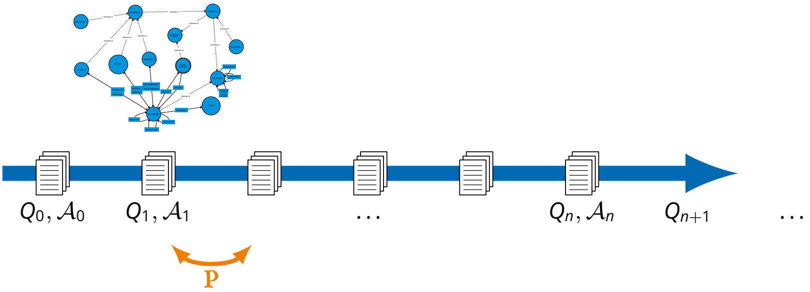

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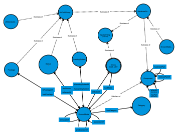

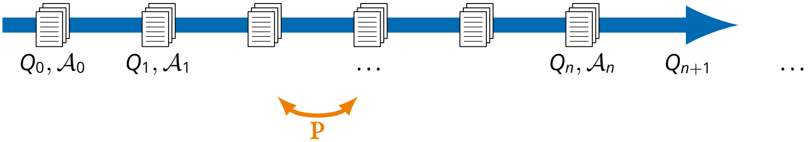

DL-Lite

- Guess additional information $\mathbf{P}$
- Do not construct $\mathbf{W}$ and $\mathbf{A}$ explicitly
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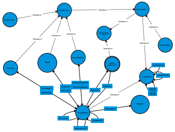

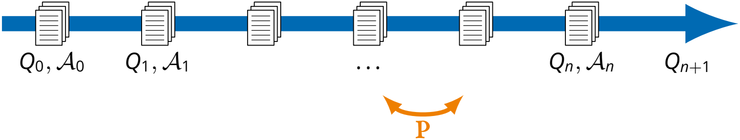

DL-Lite

AC^0 | NC^1 | NP | PSPACE

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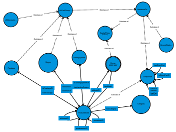

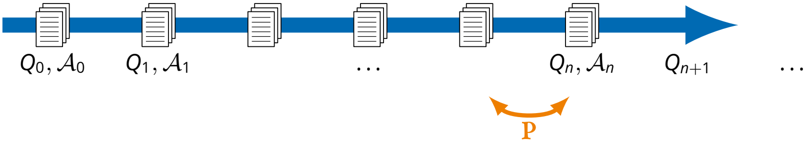

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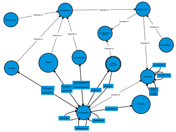

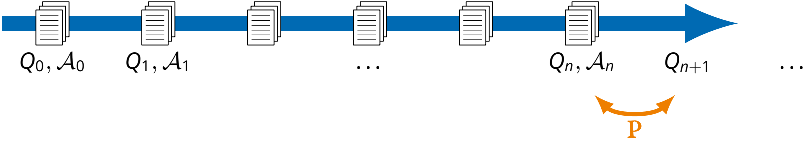

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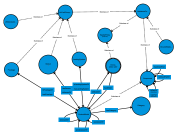

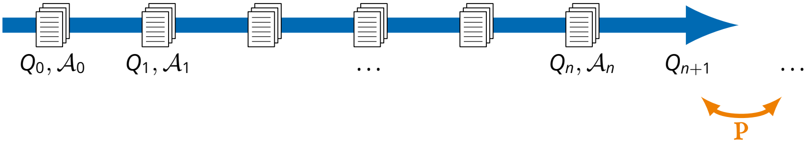

DL-Lite AC^0 | NC^1 | NP | PSPACE

- Rewrite the R-satisfiability check for $Q_{\mathbf{A}(i)}$ into a first-order query $Q_i^{\mathcal{O},\mathbf{P}}$ and answer it over the database $\mathcal{A}_i$

DL-Lite

AC^0 | NC^1 | NP | PSPACE

- Rewrite the R-satisfiability check for $Q_{\mathbf{A}(i)}$ into a first-order query $Q_i^{\mathcal{O},\mathbf{P}}$ and answer it over the database $\mathcal{A}_i$
- Use an ALOGTIME Turing machine for T-satisfiability

DL-Lite

AC^0 | NC^1 | NP | PSPACE

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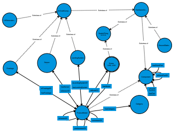
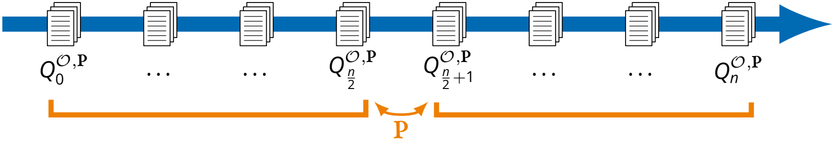
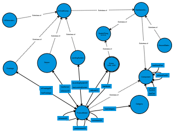


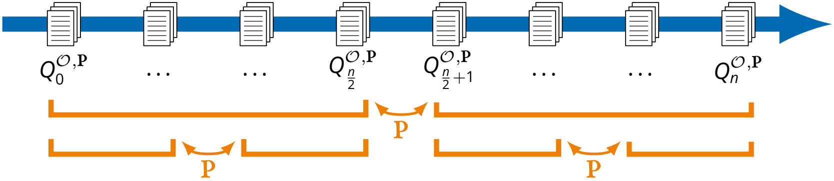


DL-Lite

AC^0 | **NC^1** | NP | PSPACE

- Rewrite the R-satisfiability check for $Q_{\mathbf{A}(i)}$ into a first-order query $Q_i^{\mathcal{O},\mathbf{P}}$ and answer it over the database $\mathcal{A}_i$
- Use an ALogTime Turing machine for T-satisfiability





DL-Lite

AC^0 | NC^1 | NP | PSPACE

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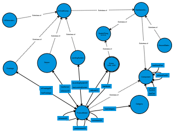

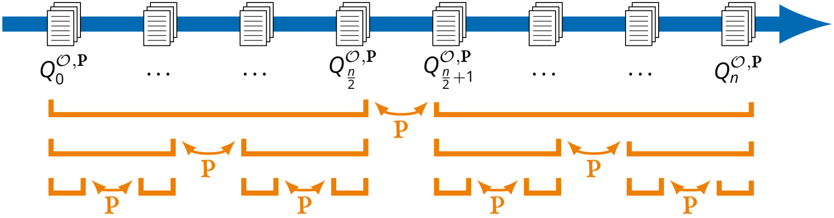

Negation

Disallowing negation in TCQs:

Description logic	Data complexity 0	1	2	3	Combined complexity 0	1	2	3
DL-Lite	AC^0				NP			
$\mathcal{EL}$	P				NP			
$\mathcal{ALC}$	coNP				Exp			
$\mathcal{SHIQ}$	coNP				2Exp			

(Borgwardt, Lippmann, and Thost 2015; Bourgaux and Turhan 2017)

Negation

Disallowing negation in TCQs:

Description logic	Data complexity				Combined complexity			
	0	1	2	3	0	1	2	3
DL-Lite	bounded history encoding				NP			
$\mathcal{EL}$					NP			
$\mathcal{ALC}$	coNP				Exp			
$\mathcal{SHIQ}$	coNP				2Exp			

(Borgwardt, Lippmann, and Thost 2015; Bourgaux and Turhan 2017)

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Disallowing negation in TCQs:

Description logic	Data complexity	Combined complexity
	0 1 2 3	0 1 2 3
DL-Lite	bounded history encoding	NP
$\mathcal{EL}$		NP
$\mathcal{ALC}$	coNP	Exp
$\mathcal{SHIQ}$	coNP	2Exp

Closed-world negation?

(Borgwardt, Lippmann, and Thost 2015; Bourgaux and Turhan 2017)

Metric Temporal Operators

- Refer to specific time intervals, e.g. “in the last 10 minutes”:

$\Diamond_{[-10,0]}\boxed{\exists f.\,\mathsf{hasLocation}(d,f) \land \mathsf{Hauptbahnhof}(f)}$

(Baader, Borgwardt, Koopmann, Ozaki, and Thost 2017; Brandt, Kalaycı, Kontchakov, Ryzhikov, Xiao, and Zakharyaschev 2017; Gutiérrez-Basulto, Jung, and Ozaki 2016; Thost 2018)

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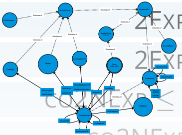
$$\Diamond_{[-10,0]} \boxed{\exists f.\, \mathsf{hasLocation}(d,f) \land \mathsf{Hauptbahnhof}(f)}$$

- Often cause an exponential blow-up ...
- ... unless restricted to intervals $[0,c]$, $[c,\infty)$, $[-c,0]$, $(-\infty,-c]$

(Baader, Borgwardt, Koopmann, Ozaki, and Thost 2017; Brandt, Kalaycı, Kontchakov, Ryzhikov, Xiao, and Zakharyaschev 2017; Gutiérrez-Basulto, Jung, and Ozaki 2016; Thost 2018)

Outlook

Description logic	Data complexity 0	1	2	3	Combined complexity 0	1	2	3
DL-Lite	AC^0	NC^1			NP	PSPACE		
$\mathcal{EL}$	P		coNP		NP	PSPACE		coNExp
$\mathcal{ALC}$	coNP				Exp		coNExp	2Exp
		NP		$\leq$ Exp	2Exp			
		NP $\leq$? $\leq$ Exp			2Exp			
					coNExp $\leq$? $\leq$ dec.			
					co2NExp $\leq$?			



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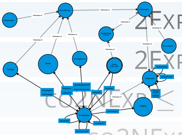
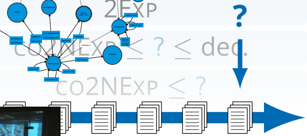
Outlook

Description logic	Data complexity 0	1	2	3	Combined complexity 0	1	2	3
DL-Lite	AC^0	NC^1			NP	PSPACE		
$\mathcal{EL}$	P		CONP		NP	PSPACE		CONEXP
$\mathcal{ALC}$	CONP				EXP		CONEXP	2EXP
	NP			$\leq$ EXP		2EXP		
	NP $\leq$? $\leq$ EXP					2EXP		
						CO2NEXP $\leq$? $\leq$ dec.		
						CO2NEXP $\leq$?		





Thank you!

References I

Baader, Franz, Stefan Borgwardt, Patrick Koopmann, Ana Ozaki, and Veronika Thost (2017). “Metric Temporal Description Logics with Interval-Rigid Names”. In: *Proc. FroCoS'17*. Volume 10483. LNCS, pages 60–76.

Baader, Franz, Stefan Borgwardt, and Marcel Lippmann (2013). “Temporalizing Ontology-Based Data Access”. In: *Proc. CADE'13*. Volume 7898. LNCS, pages 330–344.

— (2015a). “Temporal Conjunctive Queries in Expressive Description Logics with Transitive Roles”. In: *Proc. AI'15*. Volume 9457. LNAI, pages 21–33.

— (2015b). “Temporal Query Entailment in the Description Logic $\mathcal{SHQ}$”. In: *J. Web Semant.* 33, pages 71–93.

Baader, Franz, Silvio Ghilardi, and Carsten Lutz (2012). “LTL over Description Logic Axioms”. In: *ACM T. Comput. Log.* 13.3, 21:1–21:32.

Borgwardt, Stefan, Marcel Lippmann, and Veronika Thost (2015). “Temporalizing Rewritable Query Languages over Knowledge Bases”. In: *J. Web Semant.* 33, pages 50–70.

Borgwardt, Stefan and Veronika Thost (2015a). “Temporal Query Answering in *DL-Lite* with Negation”. In: *Proc. GCAI'15*. Volume 36. EPiC, pages 51–65.

— (2015b). “Temporal Query Answering in the Description Logic $\mathcal{EL}$”. In: *Proc. IJCAI'15*, pages 2819–2825.

Bourgaux, Camille and Anni-Yasmin Turhan (2017). “Temporal Query Answering in DL-Lite over Inconsistent Data”. In: *Proc. ISWC'17*. Volume 10587. LNCS, pages 121–137.

References II

Brandt, Sebastian, Elem Güzel Kalaycı, Roman Kontchakov, Vladislav Ryzhikov, Guohui Xiao, and Michael Zakharyaschev (2017). “Ontology-Based Data Access with a Horn Fragment of Metric Temporal Logic”. In: *Proc. AAAI’17*, pages 1070–1076.

Gabbay, Dov M., Agi Kurucz, Frank Wolter, and Michael Zakharyaschev (2003). *Many-Dimensional Modal Logics: Theory and Applications*. Volume 148. Studies in Logic and the Foundations of Mathematics.

Gutiérrez-Basulto, Víctor, Jean Christoph Jung, and Ana Ozaki (2016). “On Metric Temporal Description Logics”. In: *Proc. ECAI’16*. Volume 285. FAIA, pages 837–845.

Thost, Veronika (2017). “News on Temporal Conjunctive Queries”. In: *Joint Proc. of the Web Stream Processing workshop (WSP’17) and the 2nd Int. Workshop on Ontology Modularity, Contextuality, and Evolution (WOMoCoE’17)*. Volume 1936. CEUR-WS, pages 1–16.

— (2018). “Metric Temporal Extensions of *DL-Lite* and Interval-Rigid Names”. In: *Proc. KR’18*. To appear.

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