

Ontology-Mediated Queries for Probabilistic Databases

*Stefan Borgwardt*¹, İsmail İlkan Ceylan¹, Thomas Lukasiewicz²

Melbourne, 20/08/2017

1



TECHNISCHE
UNIVERSITÄT
DRESDEN

2



UNIVERSITY OF
OXFORD

A photograph of a large, curved library with multiple levels of bookshelves filled with books. The lighting is warm and the perspective is from within the library, looking down the curve.

Google's Knowledge Vault

NELL

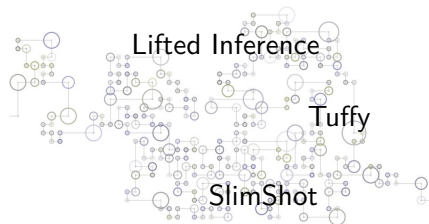
DeepDive



Google's Knowledge Vault

NELL

DeepDive

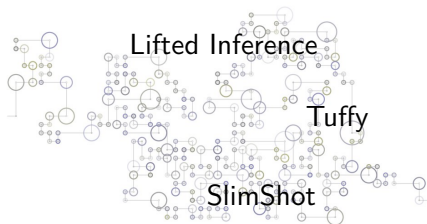




Google's Knowledge Vault

NELL

DeepDive



Probabilistic Databases (PDBs)

Writer

Banks	0.8
Hamilton	0.7
⋮	⋮

AuthorOf

Banks	Excession	0.9
Banks	Inversions	0.8
Stephenson	Anathem	0.9
⋮	⋮	

Novel

Anathem	1
Matter	0.7
⋮	⋮

Writer

Banks	0.8
Hamilton	0.7
⋮	⋮

AuthorOf

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⋮	⋮	

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Anathem	1
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⋮	⋮

Possible worlds $\mathcal{D}$: $\text{Writer}(\text{Banks})$, $\text{AuthorOf}(\text{Banks}, \text{Excession})$, ...

Finite

Writer

Banks	0.8
Hamilton	0.7
$\vdots$	$\vdots$

AuthorOf

Banks	Excession	0.9
Banks	Inversions	0.8
Stephenson	Anathem	0.9
$\vdots$	$\vdots$	

Novel

Anathem	1
Matter	0.7
$\vdots$	$\vdots$

Possible worlds $\mathcal{D}$: $\text{Writer}(\text{Banks})$, $\text{AuthorOf}(\text{Banks}, \text{Excession})$, ...

Probability $P(\mathcal{D})$: 0.8 · (1 − 0.9) · ...

Finite

Tuple-independent

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Tuple-independent

Probabilistic query evaluation

Q: $\exists x. \text{AuthorOf}(\text{Banks}, x)$

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Probability $P(\mathcal{D})$: 0.8 · $(1 - 0.9)$ · ...

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Probabilistic query evaluation

$Q: \exists x. \text{AuthorOf}(\text{Banks}, x)$

$$P(Q) = \sum_{\mathcal{D} \models Q} P(\mathcal{D})$$

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$Q: \exists x. \text{AuthorOf}(\text{Banks}, x)$

$$P(Q) = \sum_{\mathcal{D} \models Q} P(\mathcal{D}) = 0.8 \cdot (1 - 0.9) \cdot 0.8 \cdot \dots + \dots = 0.98$$

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$Q: \exists x. \text{AuthorOf}(\text{Banks}, x)$

$$P(Q) = \sum_{\mathcal{D} \models Q} P(\mathcal{D}) = 0.8 \cdot (1 - 0.9) \cdot 0.8 \cdot \dots + \dots = 0.98$$

$$P(\exists x. \text{AuthorOf}(\text{Banks}, x) \wedge \text{Novel}(x)) = 0$$

Closed-world

Open-World Probabilistic Databases (OpenPDBs)

(Ceylan, Darwiche, and Van den Broeck 2016)

(IJCAI Talk: Thursday, August 24, 17:30, Session SIS-ML, Room 204)

$$\text{OpenPDB} = \text{PDB} + \lambda$$
$$P(\text{Novel}(\text{Excession})) \in [0, \lambda]$$

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$\leadsto$ credal set of probability distributions P

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Lower and upper probability

$$\underline{P}(Q) = \min_P P(Q) \quad \bar{P}(Q) = \max_P P(Q)$$

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Excession	[0, 0.7]
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$$\overline{P}(\exists x. \text{AuthorOf}(\text{Banks}, x) \wedge \text{Novel}(x)) = 0.8372$$

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Novel

Anathem	1
Matter	0.7
Excession	[0, 0.7]
Inversions	[0, 0.7]

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$$P(\text{Novel}(\text{Excession})) \in [0, \lambda]$$

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$$\overline{P}(\exists x. \text{AuthorOf}(\text{Banks}, x) \wedge \text{Novel}(x)) = 0.8372$$

Data complexity dichotomy

Deciding $\overline{P}(Q) > p$ is either in P (“safe”) or PP -complete (“unsafe”).
(Ceylan, Darwiche, and Van den Broeck 2016; Dalvi and Suciu 2012)

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Writer(Stephenson)

[0, 0.7]

Writer(Anathem)

[0, 0.7]

Writer

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Writer(Stephenson)

[0, 0.7]

Writer(Anathem)

[0, 0.7]

$\text{AuthorOf}(x, y) \wedge \text{Novel}(y) \rightarrow \text{Writer}(x) \quad \text{Writer}(x) \wedge \text{Novel}(x) \rightarrow \perp$

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Writer(Anathem)

[0, 0.7]

$\text{AuthorOf}(x, y) \wedge \text{Novel}(y) \rightarrow \text{Writer}(x)$ $\text{Writer}(x) \wedge \text{Novel}(x) \rightarrow \perp$

Markov Logic Networks (MLNs)

$\text{Person}(x) \rightarrow \exists y. \text{ParentOf}(y, x) \wedge \text{Person}(y)$

$\text{ParentOf}(x, y) \rightarrow \text{AncestorOf}(x, y)$

$\text{ParentOf}(x, y) \wedge \text{AncestorOf}(y, z) \rightarrow \text{AncestorOf}(x, z)$

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$\text{ParentOf}(x, y) \wedge \text{AncestorOf}(y, z) \rightarrow \text{AncestorOf}(x, z)$

$P(\exists x. \text{AncestorOf}(x, x)) = 1$

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$\text{AuthorOf}(x, y) \wedge \text{Novel}(y) \rightarrow \text{Writer}(x) \quad \text{Writer}(x) \wedge \text{Novel}(x) \rightarrow \perp$

Datalog[±] Programs (Ontologies)

$\text{Person}(x) \rightarrow \exists y. \text{ParentOf}(y, x) \wedge \text{Person}(y)$

$\text{ParentOf}(x, y) \rightarrow \text{AncestorOf}(x, y)$

$\text{ParentOf}(x, y) \wedge \text{AncestorOf}(y, z) \rightarrow \text{AncestorOf}(x, z)$

$P(\exists x. \text{AncestorOf}(x, x)) = 0$

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Writer(Stephenson)

[0, 0.7]

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[0, 0.7]

$\text{AuthorOf}(x, y) \wedge \text{Novel}(y) \rightarrow \text{Writer}(x) \quad \text{Writer}(x) \wedge \text{Novel}(x) \rightarrow \perp$

Ontology-Mediated Queries (OMQs)

(Conjunctive query Q , Datalog[±] program Σ)

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Writer(Stephenson)

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Ontology-Mediated Queries (OMQs)

(Conjunctive query Q , Datalog[±] program Σ)

FO-rewritable: $\mathcal{D} \models (Q, \Sigma) \sim \mathcal{D} \models Q_{\Sigma}$

$\text{AuthorOf}(x, y) \wedge \text{Novel}(y) \rightarrow \text{Writer}(x)$

Semantics for positive OMQs

$$P(Q, \Sigma) = \sum_{\mathcal{D} \models (Q, \Sigma)} P(\mathcal{D})$$

$$\text{AuthorOf}(x, y) \wedge \text{Novel}(y) \rightarrow \text{Writer}(x)$$

Semantics for positive OMQs

$$P(Q, \Sigma) = \sum_{\mathcal{D} \models (Q, \Sigma)} P(\mathcal{D})$$

$$\underline{P}(Q, \Sigma) = \min_P P(Q, \Sigma)$$

$$\overline{P}(Q, \Sigma) = \max_P P(Q, \Sigma)$$

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$$\underline{P}(Q, \Sigma) = \min_P P(Q, \Sigma)$$

$$\overline{P}(Q, \Sigma) = \max_P P(Q, \Sigma)$$

$$\underline{P}(\text{Writer}(\text{Stephenson})) = 0.9$$

$$\overline{P}(\text{Writer}(\text{Stephenson})) = 0.9 + 0.1 \cdot 0.7 = 0.97$$

Writer

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$$\underline{P}(\text{Writer}(\text{Stephenson})) = 0.9$$

$$\overline{P}(\text{Writer}(\text{Stephenson})) = 0.9 + 0.1 \cdot 0.7 = 0.97$$

Dichotomy

For FO-rewritable positive OMQs (Q, Σ) ,

deciding $\overline{P}(Q, \Sigma) > p$ is either **in P** or **PP-complete**.

$$(Q, \Sigma) \quad \rightsquigarrow \quad Q_\Sigma \quad \rightsquigarrow \quad \overline{P}(Q_\Sigma)$$

$$(Q, \Sigma) \quad \rightsquigarrow \quad Q_\Sigma \quad \rightsquigarrow \quad \overline{P}(Q_\Sigma)$$

$\text{AuthorOf}(x, y) \wedge \text{Novel}(y) \rightarrow \text{Writer}(x)$

$\text{CharacterIn}(x, y) \wedge \text{Novel}(y) \rightarrow \text{LiteraryCharacter}(x)$

$\exists x. \text{Writer}(x) \wedge \text{LiteraryCharacter}(x)$

$$(Q, \Sigma) \quad \rightsquigarrow \quad Q_\Sigma \quad \rightsquigarrow \quad \overline{P}(Q_\Sigma)$$

$\text{AuthorOf}(x, y) \wedge \text{Novel}(y) \rightarrow \text{Writer}(x)$

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$\exists x. \text{Writer}(x) \wedge \text{LiteraryCharacter}(x)$

$\Downarrow$

$\exists x, y, z. \text{AuthorOf}(x, y) \wedge \text{Novel}(y) \wedge \text{CharacterIn}(x, z) \wedge \text{Novel}(z)$

$$(Q, \Sigma) \quad \rightsquigarrow \quad Q_\Sigma \quad \rightsquigarrow \quad \overline{P}(Q_\Sigma)$$

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$$\text{AuthorOf}(x, y) \wedge \text{Novel}(y) \rightarrow \text{Writer}(x)$$

$$\exists x, y. \text{Writer}(x) \wedge \text{AuthorOf}(x, y) \wedge \text{Novel}(y)$$

$$(Q, \Sigma) \quad \rightsquigarrow \quad Q_\Sigma \quad \rightsquigarrow \quad \overline{P}(Q_\Sigma)$$

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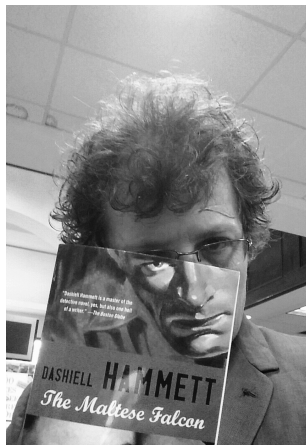
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$$\exists x, y. \text{Writer}(x) \wedge \text{AuthorOf}(x, y) \wedge \text{Novel}(y)$$

$$\Downarrow$$

$$\exists x, y. \text{AuthorOf}(x, y) \wedge \text{Novel}(y)$$

$$\text{Writer}(x) \wedge \text{Novel}(x) \rightarrow \perp$$



$$\text{Writer}(x) \wedge \text{Novel}(x) \rightarrow \perp$$

Semantics with negative constraints

$$\bar{P}(Q, \Sigma) = \max_P \frac{P(Q, \Sigma) - P(\perp, \Sigma)}{1 - P(\perp, \Sigma)}$$

$$\text{Writer}(x) \wedge \text{Novel}(x) \rightarrow \perp$$

Semantics with negative constraints

$$\bar{P}(Q, \Sigma) = \max_P \{P(Q, \Sigma) \mid P_{>0} \text{ consistent with } \Sigma\}$$

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Semantics with negative constraints

$$\overline{P}(Q, \Sigma) = \max_P \{P(Q, \Sigma) \mid P_{>0} \text{ consistent with } \Sigma\}$$

$$\underline{P}(\text{Writer}(\text{Anathem})) = 0$$

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Banks	0.8
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$$\text{Writer}(x) \wedge \text{Novel}(x) \rightarrow \perp$$

Semantics with negative constraints

$$\bar{P}(Q, \Sigma) = \max_P \{P(Q, \Sigma) \mid P_{>0} \text{ consistent with } \Sigma\}$$

$$\underline{P}(\text{Writer}(\text{Anathem})) = 0$$

$$\bar{P}(\text{Writer}(\text{Anathem})) = 0$$

Hardness result

For guarded Datalog programs,

deciding $\bar{P}(Q, \Sigma) > p$ is **NP^{PP}-complete** (**PP-complete** for PDBs).

$$\exists x_1, \dots, x_\ell. C^c y_1, \dots, y_m. \phi$$

Summary

Enriched OpenPDBs with ontology-based semantics

Lifted P/PP dichotomy for FO-rewritable positive OMQs

Negative constraints make it NP^{PP} -hard for guarded Datalog

Combined complexity results: $PP^{NP}/NP^{PP}/\dots/2-ExpTime$

Summary

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Open problems

Positive (Q, Σ) not FO-rewritable $\Rightarrow PP$ -hard? (Jung and Lutz 2012)

(Q, Σ) FO-rewritable $\Rightarrow$ dichotomy?

Knowledge compilation or approximation techniques for NP^{PP} -problems?

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IJCAI Talk: Most Probable Explanations for Probabilistic Database Queries

Wednesday, August 23, 11:45, Session KR-DLO2, Room 217

Summary

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Combined complexity results: $PP^{NP}/NP^{PP}/\dots/2-ExpTime$

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IJCAI Talk: Most Probable Explanations for Probabilistic Database Queries

Wednesday, August 23, 11:45, Session KR-DLO2, Room 217

Thank you!

- Borgwardt, Stefan, İsmail İlkan Ceylan, and Thomas Lukasiewicz (2017). "Ontology-Mediated Queries for Probabilistic Databases". In: *Proc. of the 31st AAAI Conf. on Artificial Intelligence (AAAI'17)*, pages 1063–1069.
- Ceylan, İsmail İlkan, Adnan Darwiche, and Guy Van den Broeck (2016). "Open-World Probabilistic Databases". In: *Proc. of the 15th Int. Conf. on Principles of Knowledge Representation and Reasoning (KR'16)*, pages 339–348.
- Dalvi, Nilesch and Dan Suciu (2012). "The Dichotomy of Probabilistic Inference for Unions of Conjunctive Queries". In: *Journal of the ACM* 59.6, 30:1–30:87.
- Jung, Jean Christoph and Carsten Lutz (2012). "Ontology-Based Access to Probabilistic Data with OWL QL". In: *Proc. of the 11th Int. Semantic Web Conf. (ISWC'12)*, pages 182–197.

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