Consistent Query Answering with Respect to Primary Keys

[Some] Past Research and Future Challenges

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Inconsistent Data

Perrey Reeves

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From Wikipedia, the free encyclopedia

Perrey Reeves (born 1970 or 1971 (age 52–53))[1] is an American film and television actress. She is best known for her recurring role as Melissa Gold on the television series *Entourage* from 2004 to 2011 and Marissa Jones in the 2003 comedy *Old School*.

Perrey Reeves

Early life [edit]

Reeves was born in New York City and raised in New Hampshire,[2] the daughter of Dr. Alexander Reeves, a

Inconsistent Databases

ACTORS	<u>Name</u>	Gender	Age
	Jolie	F	48
	Pitt	M	59
	Pitt	M	60

Every actor has, at most, one gender and one age:

`ACTORS PRIMARY KEY(Name).`

Data cleaning takes time (and money). Can we already obtain "reliable" information by querying the inconsistent database?

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Querying Inconsistent Databases

For ease of presentation, all queries return a Boolean (true/false).

ACTORS

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Jolie	F	48
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- Is Pitt's age 60?

$\exists y\,(\text{ACTORS}(\underline{\text{Pitt}}, y, 60))$ is "possibly false".

- Is Pitt older than Jolie?

$$\exists y \exists z \exists v \exists w \left(\begin{array}{l} \text{ACTORS}(\underline{\text{Pitt}}, y, z) \wedge \\ \text{ACTORS}(\underline{\text{Jolie}}, v, w) \wedge z > w \end{array} \right) \text{ is "certainly true".}$$

A block is a maximal set of tuples of the same relation that agree on their primary key (blocks are separated by dashed lines).
A repair (or possible world) is obtained by picking a single tuple from each block.

With this notion, "certainly true" means "true in every repair".

If 2 ages are stored for n actors, there are at least 2^n repairs.

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Consistent Query Answering for Primary Keys

Given a Boolean query Q, define the following decision problem:

Problem CERTAINTY(Q)

Input: A database instance D that may violate primary-key constraints.

Question: Is Q true in every repair of D?

Example

If $Q_{60} = \exists y\,(\text{ACTORS}(\underline{\text{Pitt}}, y, 60))$, then the answer to CERTAINTY(Q_{60}) is "no" on our example database.

Remark

We assume that each relation name has a fixed primary key. Primary-key positions will be underlined. Primary keys can thus be derived from the query.

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Proposition

CERTAINTY(Q) *is in* coNP *for first-order queries* Q.

Proof.

A "'no" certificate is a repair that falsifies Q. $\square$

CERTAINTY(Q_{60}) is in FO, as the following are equivalent for every database instance D:

1. Q is true in every repair of D;
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The Good, the Bad and the Ugly

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For $Q_{\text{good}} = \exists y\,(\text{ACTORS}(\underline{\text{Pitt}}, y, 60))$, *the decision problem* $\text{CERTAINTY}(Q_{\text{good}})$ *is in* FO.

Theorem ([W., 2010])

For $Q_{\text{bad}} = \exists x \exists y\,(R(\underline{x}, y) \wedge S(\underline{y}, x))$, *the decision problem* $\text{CERTAINTY}(Q_{\text{bad}})$ *is in* $\text{P} \setminus \text{FO}$ *(later, it was proven* L-*complete).*

Theorem ([Chomicki and Marcinkowski, 2005])

For $Q_{\text{ugly}} = \exists x_1 \exists x_2 \exists z\,(\text{ACTORS}(\underline{x_1}, \text{M}, z) \wedge \text{ACTORS}(\underline{x_2}, \text{F}, z))$, *the decision problem* $\text{CERTAINTY}(Q_{\text{ugly}})$ *is* coNP-*complete.*

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Research Agenda

- We aim to go beyond the task of determining CERTAINTY(Q) for individual queries Q.
- For "reasonable" classes $\mathcal{C}$ of queries, write an algorithm for the following problem:

Complexity Classification Task

Input: A query Q in the class $\mathcal{C}$.

Task: The computational complexity of CERTAINTY(Q), in terms of complexity classes like FO, P, coNP-complete,...

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Which Query Classes Are "Reasonable"?

- The class of (Boolean) conjunctive queries (a.k.a. Select-Project-Join queries):

$$\exists \vec{u} \left(R_1(\underline{\vec{x}_1}, \vec{y}_1) \wedge R_2(\underline{\vec{x}_2}, \vec{y}_2) \wedge \cdots \wedge R_n(\underline{\vec{x}_n}, \vec{y}_n) \right). \qquad (1)$$

- The class of disjunctions of conjunctive queries (a.k.a. UCQ queries):

$$Q_1 \vee Q_2 \vee \cdots \vee Q_m,$$

where each Q_i is of the form (1).

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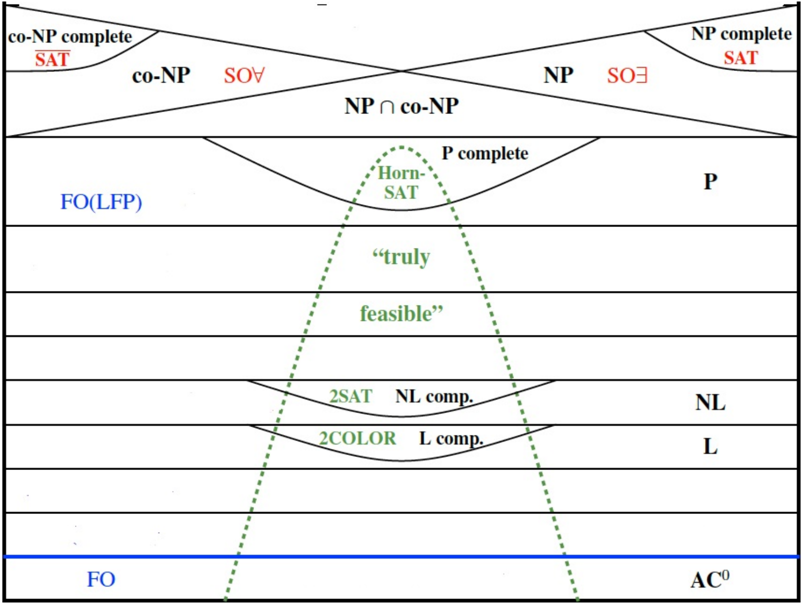

Classifying CERTAINTY(Q) in P/coNP-complete is Hard

Conjecture

If Q is a disjunction of conjunctive queries, then CERTAINTY(Q) *is in* P *or* coNP*-complete.*

Theorem ([Fontaine, 2015])

The above conjecture implies Bulatov's dichotomy theorem for the conservative constraint satisfaction problem (CSP).

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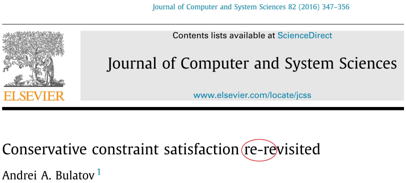
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Conservative constraint satisfaction re-revisited

Andrei A. Bulatov [1]

Is it Easier for Conjunctive Queries?

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If Q is of the form $\exists \vec{u} \left(R_1(\underline{\vec{x}_1}, \vec{y}_1) \wedge \cdots \wedge R_n(\underline{\vec{x}_n}, \vec{y}_n) \right)$, then CERTAINTY($Q$) *is in* P *or* coNP*-complete.*

Theorem ([Koutris and W., 2017])

The above conjecture holds under the assumption that $R_i \neq R_j$ whenever $i \neq j$.

Somewhat later, if was proven that for every self-join-free CQ Q, CERTAINTY(Q) is either in FO, L-complete, or coNP-complete.

Theorem ([Padmanabha et al., 2023])

The above conjecture holds under the assumption that $n = 2$.

Theorem ([Koutris et al., 2021])

The above conjecture holds for queries of the form $\exists x_1 \cdots \exists x_{n+1} \left(R_1(\underline{x_1}, x_2) \wedge R_2(\underline{x_2}, x_3) \wedge \cdots \wedge R_n(\underline{x_n}, x_{n+1}) \right)$.

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The Good Among the Good, the Bad and the Ugly

A directed graph, called attack graph, is defined for every conjunctive query.

Theorem ([Koutris and W., 2017])

Let $Q = \exists \vec{u} \left(R_1(\underline{\vec{x}_1}, \vec{y}_1) \land \cdots \land R_n(\underline{\vec{x}_n}, \vec{y}_n) \right)$ *with* $R_i \neq R_j$ *for* $i \neq j$. *Then,*

- *if Q's attack graph is acyclic, then* CERTAINTY(Q) *is in* FO;
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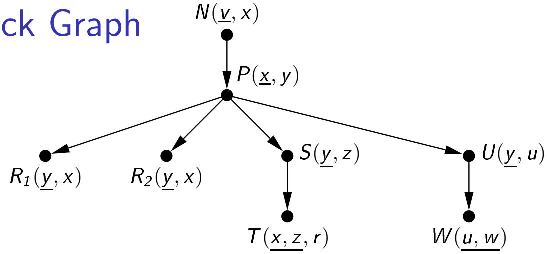
Attack Graph



$N^+ = \{v\}$

$P^+ = \{x\}$

${R_1}^+ = \{y, x, z, r, u\}$

${R_2}^+ = \{y, x, z, r, u\}$

$S^+ = \{y, x, u\}$

$U^+ = \{y, x, z, r\}$

$T^+ = \{x, z, y, u\}$

$W^+ = \{u, w\}$

S^+, e.g., is the closure of S's key w.r.t. all other FDs.
S can attack with $z \notin S^+$.

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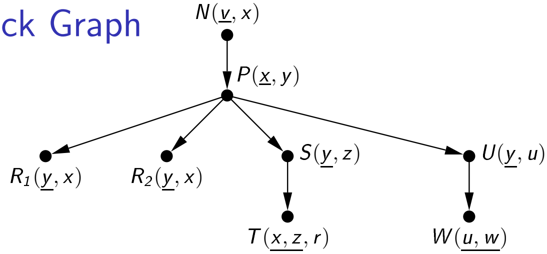

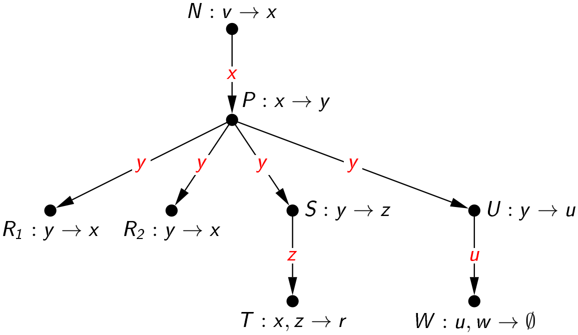

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Attack Graph and (Consistent) First-Order Rewriting

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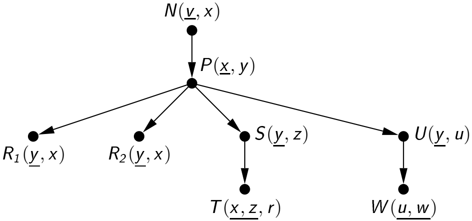

We construct a first-order formula φ_N such that for every database:

φ_N is true in the database $\iff$ Q is true in every repair.

$$\varphi_N := \exists v \left(\exists x \left(N(\underline{v}, x) \right) \land \neg \exists x \left(N(\underline{v}, x) \land \neg \varphi_P(v, x) \right) \right),$$

where $\varphi_P(v, x)$ is a rewriting of the conjunctive query whose atoms are the atoms of Q except $N(\underline{v}, x)$, in which variables v and x are free.
The empty query rewrites to `true`.

Attack Graph and (Consistent) First-Order Rewriting

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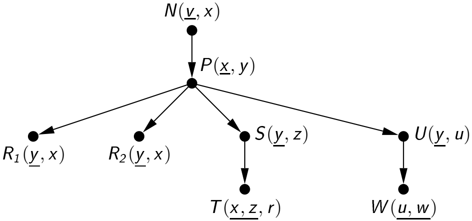

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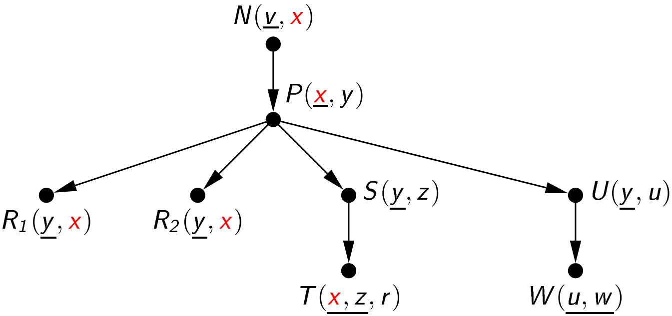
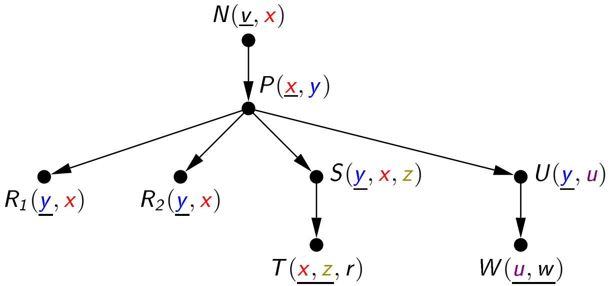
Attack Graph $\neq$ Join Tree



The subgraph induced by atoms that contain x is not connected.

Attack Graph that Is a Join Tree



Moreover, every internal node V has zero indegree in the attack graph of the subquery rooted at V ($V \in \{P, S, U\}$).
Such a join tree is called a Pair-Pruning Join Tree (PPJT).
Yannakakis' algorithm extends to the inconsistent setting:

Theorem ([Fan et al., 2023])

If Q has a PPJT, then CERTAINTY(Q) *is in* LIN *(i.e., problems solvable in linear time).*

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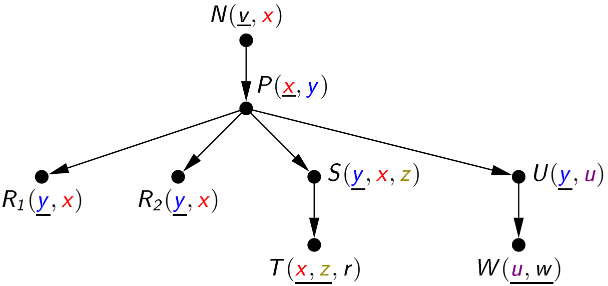

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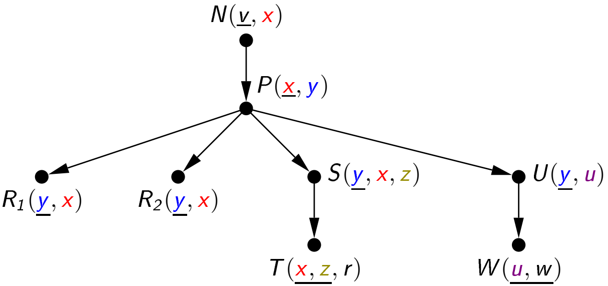

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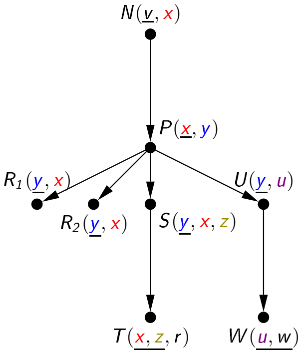
Yannakakis+Pruning



$$T^{\text{join}}(x, z) \leftarrow T(\underline{x, z}, r)$$
$$W^{\text{join}}(u) \leftarrow W(\underline{u, w})$$

$$\mathit{Answer}(\text{yes}) \leftarrow N(\underline{v}, x) \land \neg N^{\text{fadingkey}}(v)$$
$$N^{\text{fadingkey}}(v) \leftarrow N(\underline{v}, x) \land \neg P^{\text{join}}(x)$$

$$P^{\text{join}}(x) \leftarrow P(\underline{x}, y) \land \neg P^{\text{fadingkey}}(x)$$
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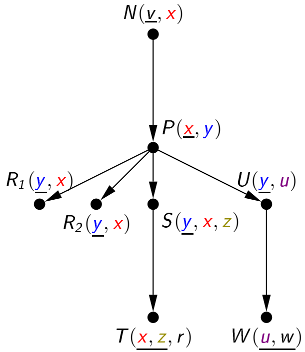

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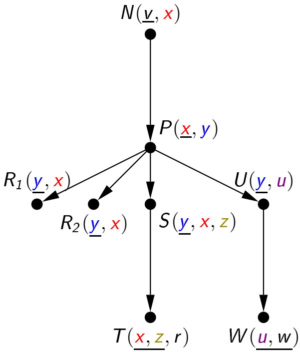

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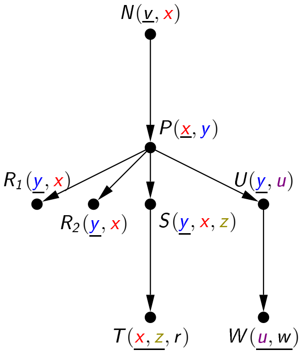

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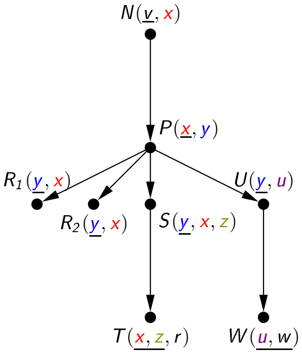

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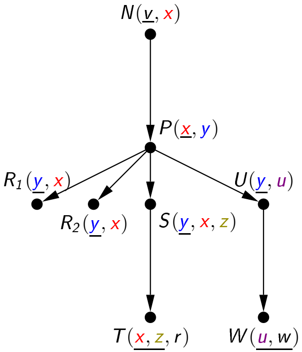

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Observation Regarding Correctness

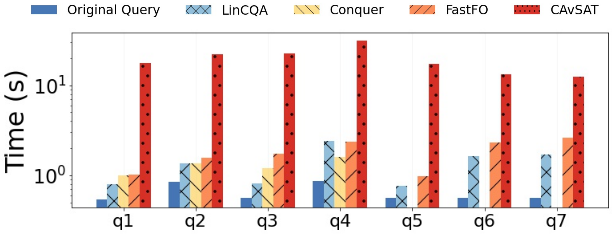
R_i-blocks of size ≥ 2 can be ignored. For example,

$$R_1 \begin{array}{|cc} \underline{y} & x \\ \hline a & c_1 \\ a & c_2 \end{array} \qquad R_2 \begin{array}{|cc} \underline{y} & x \\ \hline a & c_1 \\ a & c_2 \end{array}$$

To construct a repair that falsifies the query, pick $R_1(\underline{a}, c_i)$ and $R_2(\underline{a}, c_j)$ such that $c_i \neq c_j$.

LinCQA

- LinCQA is a system that takes as input any query with a PPJT and outputs rewritings in both SQL and non-recursive Datalog with negation.
- `https://github.com/xiatingouyang/LinCQA/`
- See [Fan et al., 2023] for experiments.



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Range Consistent Query Answering [Arenas et al., 2001]

For queries returning numbers instead of Booleans.

For ease of presentation, all queries return a single number.

ACTORS

Name	Gender	Age
Jolie	F	48
Pitt	F	59
Pitt	M	60
Reeves	F	52
Reeves	F	53

Get the age of the oldest actress:

$$\mathtt{MAX}(z) \leftarrow \mathsf{ACTORS}(\underline{x}, \mathsf{F}, z).$$

- The lowest answer across all repairs is $\mathtt{MAX}(\{48, 52\}) = 52$;
- the greatest answer across all repairs is $\mathtt{MAX}(\{48, 59, 53\}) = 59$;
- the interval $[52, 59]$ is called the range consistent answer.

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Formal Setting

- Numerical terms $f()$ expressible in the (safe) rule format

$$\texttt{AGG}(r) \leftarrow R_1(\underline{\vec{x}_1}, \vec{y}_1) \wedge R_2(\underline{\vec{x}_2}, \vec{y}_2) \wedge \cdots \wedge R_n(\underline{\vec{x}_n}, \vec{y}_n), \qquad (2)$$

  where r is either a numerical variable or a constant, and AGG is an aggregate operator (e.g., MAX, MIN, SUM, COUNT, AVG); assume $R_i \neq R_j$ if $i \neq j$.
- Given a database instance, let $f^+()$ and $f^-()$ be, respectively, the greatest and smallest values of $f()$ across all repairs.
- Aggregate logic $\mathcal{L}_{\mathrm{aggr}}$ [Hella et al., 2001]: FOL + aggregation.
- Question in [Fuxman, 2007] and [Dixit and Kolaitis, 2022]:

  When can $f^+()$ and $f^-()$ be expressed in $\mathcal{L}_{\mathrm{aggr}}$?

  1. $f^+()$ and $f^-()$ are not expressible in $\mathcal{L}_{\mathrm{aggr}}$ if the attack graph of (2) is cyclic (because queries in $\mathcal{L}_{\mathrm{aggr}}$ are Hanf-local).
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Rewriting Example

$$\texttt{MAX}(z) \leftarrow \mathsf{ACTORS}(\underline{x}, \mathsf{F}, z).$$

- Upper bound rewriting:

$$\mathsf{UB}(\texttt{MAX}(z)) \leftarrow \mathsf{ACTORS}(\underline{x}, \mathsf{F}, z)$$

- Lower bound rewriting:

$$\begin{aligned}
\mathsf{POSSIBLE_M}(x) &\leftarrow \mathsf{ACTORS}(\underline{x}, \mathsf{M}, z)\\
\mathsf{CERTAIN_F}(x, z) &\leftarrow \mathsf{ACTORS}(\underline{x}, \mathsf{F}, z), \neg\mathsf{POSSIBLE_M}(x)\\
\mathsf{L}(x, \texttt{MIN}(z)) &\leftarrow \mathsf{CERTAIN_F}(\underline{x}, z)\\
\mathsf{LB}(\texttt{MAX}(z)) &\leftarrow \mathsf{L}(x, z)
\end{aligned}$$

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Counting

Given a Boolean query Q, define the following counting problem:

Problem $\sharp$CERTAINTY(Q)

Input: A database instance that may violate primary-key constraints.

Question: How many repairs of satisfy Q?

Complexity Classification Task

Input: A self-join-free Boolean conjunctive query Q.

Task: Determine lower and upper complexity bounds on the complexity of $\sharp$CERTAINTY(q), in terms of common complexity classes like FP and $\sharp$P.

- Solved in [Maslowski and W., 2013] and generalized to FDs in [Calautti et al., 2022].
- Same problem as query answering in block-independent disjoint (BID) probabilistic databases under the restriction that in every block $\mathbf{b}$, every tuple has probability $\frac{1}{|\mathbf{b}|}$.

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BID Databases

Every input to CERTAINTY(Q) is a block-independent disjoint database without probabilities (or with uniform probabilities).

☞ Inconsistency is not only a burden, but also a chance. [1]

Researchers:

	Name	Affiliation	P
t_1^1	Fred	U. Washington	$p_1^1 = 0.3$
t_1^2		U. Wisconsin	$p_1^2 = 0.2$
t_1^3		Y! Research	$p_1^3 = 0.5$
t_2^1	Sue	U. Washington	$p_2^1 = 1.0$
t_3^1	John	U. Wisconsin	$p_3^1 = 0.7$
t_3^2		U. Washington	$p_3^2 = 0.3$
t_4^1	Frank	Y! Research	$p_4^1 = 0.9$
t_4^2		M. Research	$p_4^2 = 0.1$

[1] Inspired by [Kern-Isberner and Lukasiewicz, 2017]. The image is from [Dalvi et al., 2009].

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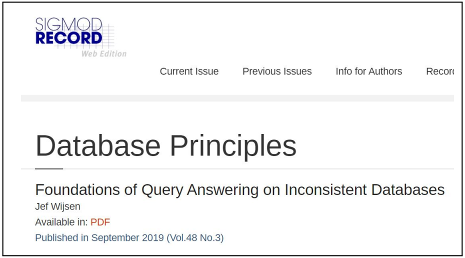
Concluding Remarks

Consistent Query Answering is an active research area since [Arenas et al., 1999]:

- Database repairing w.r.t. different classes of constraints
- Database repairing and data exchange
- Database repairing and approximations
- Database repairing and preferences
- Database repairing and implementations
- Database repairing and database management systems
- Consistent query answering for queries with negation
- Consistent query answering in description logics
- Consistent query answering over graph databases
- ...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Database Principles

Foundations of Query Answering on Inconsistent Databases
Jef Wijsen
Available in: PDF
Published in September 2019 (Vol.48 No.3)

Communications of the ACM, March 2024

research

Check for updates

DOI:10.1145/3624717

Deploying possible world semantics and the challenge of computing the certain answers to queries.

BY BENNY KIMELFELD AND PHOKION G. KOLAITIS

A Unifying Framework for Incompleteness, Inconsistency, and Uncertainty in Databases

DATABASES ARE OFTEN assumed to have definite content. The reality, though, is the database at hand may be deficient due to missing, invalid, or uncertain information. As a simple illustration, the

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semantic

Thanks!

FYI, Brad Pitt celebrated his 60th birthday on December 18, 2023.

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