Towards a Foundation of Data Currency

Jef Wijsen

University of Mons

Joint work with Wenfei Fan and Floris Geerts, University of Edinburgh

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Background/Motivation

- "The problem with data is that its quality quickly degenerates over time. Experts say 2 percent of records in a customer file become obsolete in one month because customers die, divorce, marry, and move." [Eck02]
- Often no reliable timestamps.
- How can we decide the "current truth" of a Boolean query?

Outline

Caveat

- Simplified version of the currency model proposed at PODS 2011 [FGW11].
- But the simplification maintains lower and upper complexity bounds of the problems presented.

Outline

Ordered Relation

Ordered relation $(I, \prec)$

Relation I equipped with a currency order $\prec$ such that:

- distinct tuples that agree on the primary key are comparable under $\prec$; and
- tuples that disagree on the primary key are incomparable.

Example

EMP	<u>*FN*</u>	<u>*LN*</u>	*Addr*	*Sal*	*Stat*
t_1:	Mary	Smith	2 Small St	50k	single
t_2:	Mary	Smith	10 Elm Ave	80k	married
t_3:	Mary	Smith	6 Main St	50k	married
t_4:	Bob	Luth	8 Cowan St	55k	married
t_5:	Bob	Luth	8 Drum St	80k	married

$t_1 \prec t_3 \prec t_2$

$t_4 \prec t_5$

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$t_1 \prec t_3 \prec t_2$

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There is a unique present.

Present

Present [relation]

Relation obtained by selecting all greatest tuples.

Example

EMP

FN	*LN*	*Addr*	*Sal*	*Stat*
Mary	Smith	10 Elm Ave	80k	married
Bob	Luth	8 Drum St	80k	married

Unordered Relation

Unordered relation

A relation in which primary keys need not be satisfied.
No currency order.

Example

EMP	*FN*	*LN*	*Addr*	*Sal*	*Stat*
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This leaves six possible presents.

[Currently] Certain

Completion (of an unordered relation)

Ordered relation obtained by adding a currency order $\prec$ to an unordered relation.
Every completion gives a possible present.

Definition

A Boolean query is [currently] certain if it is true in each possible present.

Certainty

It is certain that *"Bob is married."*

Certainty

The problem of certainty

For any fixed Boolean first-order query q, CERTAINTY(q) is the following problem:

Input An unordered relation

Question Is q [currently] certain?

Certainty

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For any fixed Boolean first-order query q, CERTAINTY(q) is the following problem:

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Data complexity

- CERTAINTY(q) is in **coNP**.
- There exists a Boolean conjunctive query q such that CERTAINTY(q) is **coNP**-complete.

Outline

1. Data Currency Model
   - Basic Model
   - Extension: Currency Constraints
   - Extension: Copying
2. More on CERTAINTY(q)
   - Deciding FO Definability of CERTAINTY(q)
   - Technical Development
   - Discussion and Extensions

Currency Constraints

Definition

Currency constraints are denial constraints that restrict the set of legal completions (and hence restrict the set of possible presents).

Currency constraints

- Salaries don't decrease.

$$\neg\exists s\exists t\big(s.FN = t.FN \wedge s.LN = t.LN \wedge \\ s.Sal < t.Sal \wedge t \prec s\big)$$

- Mary never divorced.

$$\neg\exists s\exists t\big(s.FN = t.FN = \text{Mary} \wedge s.LN = t.LN = \text{Smith} \wedge \\ s.Stat = \text{single} \wedge t.Stat = \text{married} \wedge t \prec s\big)$$

Consistent

Consistency w.r.t. a set Σ of denials

We call an unordered relation I consistent if it has a consistent completion (i.e., if $(I, \prec) \models \Sigma$ for some currency order $\prec$ on I).

Inconsistency

EMP	$\underline{FN}$	$\underline{LN}$	$Addr$	Sal	$Stat$
s_1:	Mary	Smith	2 Small St	80k	single
s_2:	Mary	Smith	10 Elm Ave	50k	married

$$\neg\exists s \exists t \big(s.FN = t.FN \wedge s.LN = t.LN \wedge \\ s.Sal < t.Sal \wedge t \prec s \big)$$

$$\neg\exists s \exists t \big(s.FN = t.FN = \text{Mary} \wedge s.LN = t.LN = \text{Smith} \wedge \\ s.Stat = \text{single} \wedge t.Stat = \text{married} \wedge t \prec s \big)$$

Consistency

The problem of consistency

For any fixed set Σ of currency constraints, CONSISTENCY(Σ) is the following problem:

Input An unordered relation I

Question Is I consistent?

Consistency

The problem of consistency

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Question Is I consistent?

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Background/Motivation

Deciding the "current truth" (of a Boolean query) in:

Data integration: Conflicting facts are provided by a large number of sources [DBES09].

Data replication: Applications use out-of-date replicas to improve scalability, availability, and performance [GLR05].

Copying

Example

CACHE	*FN*	*LN*	*Addr*	*Sal*	*Stat*
s_1:	Mary	Smith	2 Small St	50k	single
s_2:	Mary	Smith	10 Elm Ave	70k	married

EMP	*FN*	*LN*	*Addr*	*Sal*	*Stat*
t_1:	Mary	Smith	2 Small St	60k	single
t_2:	Mary	Smith	6 Main St	60k	married

The cache is a finite set of unordered tuples.

Copying

Example

CACHE	*FN*	*LN*	*Addr*	*Sal*	*Stat*
s_1:	Mary	Smith	2 Small St	50k	single
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The cache is a finite set of unordered tuples.

Should we extend *EMP* with extra tuples from the cache in order to get the "current truth" of a Boolean query?

Compare:

- "Is Mary married?"
- "Does Mary earn 60k?"

Copying Problems

Caveat

Extending with all “cache” tuples may result in inconsistency.

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Consistent extension w.r.t. a set Σ of denials

An unordered relation can be extended with "cache" tuples.
We call such extension maximal consistent if

- it is consistent; and
- any further proper extension is inconsistent.

Copying Problems

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Extending with all "cache" tuples may result in inconsistency.

Consistent extension w.r.t. a set Σ of denials

An unordered relation can be extended with "cache" tuples.
We call such extension maximal consistent if

- it is consistent; and
- any further proper extension is inconsistent.

Don't confuse:

- Completion $\rightsquigarrow$ adding currency order $\prec$
- Extension $\rightsquigarrow$ importing "cache" tuples

Certainty Preservation

The problem of certainty preservation

For any fixed Boolean first-order query q and set Σ of currency constraints, $\mathsf{CPP}(q, \Sigma)$ is the following problem:

Input
- a consistent unordered relation in which q is [currently] certain
- a "cache"

Question Is q [currently] certain in at least one maximal consistent extension?

Certainty Preservation

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For any fixed Boolean first-order query q and set Σ of currency constraints, CPP(q, Σ) is the following problem:

Input
- a consistent unordered relation in which q is [currently] certain
- a "cache"

Question Is q [currently] certain in at least one maximal consistent extension?

Data complexity

- CPP(q, Σ) is in Σ_2^p.
- There exists a Boolean conjunctive query q and set Σ such that CPP(q, Σ) is Σ_2^p-complete.

Σ_2^p Algorithm

Outline

1. Guess an ordered relation $(I, \prec)$.
2. Verify I is an extension and $(I, \prec) \models \Sigma$ (in **P**).
3. Verify maximality, i.e., adding an extra cache tuple to I results in inconsistency (at most linearly many queries of **coNP** oracle).
4. Verify q is [currently] certain in I (one query of **coNP** oracle).

Hardness is by reduction from the complement of $\forall\exists 3CNF$.

Outline

Back to the Basic Model/Motivation

- No currency constraints.
- No copying.
- What you get if you strip off timestamps from a temporal relation.
- We have seen that even in this basic model, there exists a Boolean conjunctive query q such that CERTAINTY(q) is **coNP**-hard.
- Can we identify queries q for which CERTAINTY(q) is tractable (or, even better, first-order definable)?

Unordered Database Again

Unordered database

A database in which primary keys need not be satisfied.

Possible present

In the absence of currency constraints, a possible present is any maximal subset of tuples that satisfy primary keys.

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Every tuple was once true

R	*FN*	*LN*	*Dname*
	Mary	Smith	R&D
	Mary	Smith	MIS

T	*Dname*	*Budget*
	R&D	60K
	MIS	60K
	Toys	60K
	Toys	70K

$\rightsquigarrow$ 2×2 possible presents

Certainty

Definition

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Example

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	Mary	Smith	R&D
	Mary	Smith	MIS

T	<u>*Dname*</u>	*Budget*
	R&D	60K
	MIS	60K
	Toys	60K
	Toys	70K

$$
\begin{aligned}
q_1 &= \exists x(R(\underline{\text{Mary}, x}, \text{R\&D})) \\
q_2 &= \exists x \exists y(R(\underline{\text{Mary}, x}, y) \wedge T(\underline{y}, \text{60K}))
\end{aligned}
$$

$\rightsquigarrow$ q_1 is not certain, q_2 is certain

Problem Statement

CERTAINTY(q)

For fixed Boolean query q, the problem CERTAINTY(q) is:

Given an unordered database, is q certain?

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Complexity for conjunctive queries

- For $q_3 = \exists x \exists y \exists z (S(\underline{x}, z) \wedge T(\underline{y}, z))$,
  CERTAINTY(q_3) is **coNP**-hard.

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- CERTAINTY(q_1) is first-order expressible (see later). That is, "Is q_1 certain?" can be encoded in FO.

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CERTAINTY(q_3) is **coNP**-hard.
- CERTAINTY(q_1) is first-order expressible (see later). That is, "Is q_1 certain?" can be encoded in FO.

Research problem

Find algorithm for the following decision problem:
Given Boolean conjunctive query q,
is CERTAINTY(q) first-order expressible (and hence in $\mathbf{AC}^0$)?

State of the art

[Wij10a]

An algorithm for the following decision problem:

Given Boolean acyclic conjunctive query q without self-join, is CERTAINTY(q) first-order expressible?

If answer is "yes," we can construct the first-order expression.

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[Wij10a]

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Remaining restrictions

- q without self-join $\iff$ no duplicate relation names in q
- q acyclic $\iff$ q has a join tree

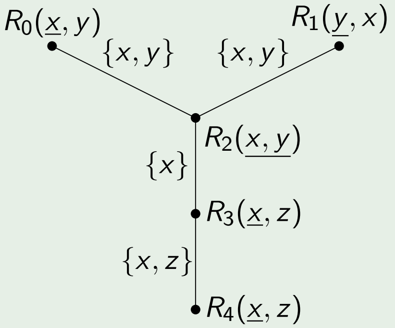
Join Tree

Definition

A join tree for conjunctive query q is an undirected tree whose vertices are the atoms of q, such that:

> Connectedness Cond. if the same variable x occurs in two distinct atoms F and G, then x occurs in each vertex on the (unique) path linking F and G.

Example



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First-order Expressibility

CERTAINTY(q_1) is first-order expressible

$$q_1 = \exists x(R(\underline{\mathsf{Mary}, x}, \mathsf{R\&D}))$$

$$\varphi_1 = \exists x\big[\, R(\underline{\mathsf{Mary}, x}, \mathsf{R\&D}) \wedge \forall z \big(\, R(\underline{\mathsf{Mary}, x}, z) \rightarrow z = \mathsf{R\&D}\big)\big]$$

For every unordered database,
q_1 certain $\iff$ φ_1 true.

First-order Expressibility

CERTAINTY(q_2) is first-order expressible

$$q_2 \quad = \quad \exists x \exists y (R(\underline{\mathrm{Mary}, x}, y) \wedge T(\underline{y}, 60\mathrm{K}))$$

$$\begin{aligned}\varphi_2 = \exists x \exists y \Big[& R(\underline{\mathrm{Mary}, x}, y) \wedge \\ & \forall y \Big(R(\underline{\mathrm{Mary}, x}, y) \rightarrow \big[T(\underline{y}, 60\mathrm{K}) \wedge \\ & \qquad \forall z (T(\underline{y}, z) \rightarrow z = 60\mathrm{K}) \big] \Big) \Big]\end{aligned}$$

For every unordered database,
q_2 certain $\iff$ φ_2 true.

Order is Important

Changing the order

$$q_2 = \exists x \exists y (T(\underline{y}, 60\mathrm{K}) \land R(\underline{\mathrm{Mary}, x}, y))$$

$$\begin{aligned}\varphi_2' = \; & \exists y \Big[T(\underline{y}, 60\mathrm{K}) \land \\ & \forall z \Big(T(\underline{y}, z) \rightarrow z = 60\mathrm{K} \land \\ & \qquad \exists x \big[R(\underline{\mathrm{Mary}, x}, y) \land \\ & \qquad \forall w \big(R(\underline{\mathrm{Mary}, x}, w) \rightarrow w = y \big) \big] \Big) \Big]\end{aligned}$$

For every unordered database, φ_2' true $\implies$ q_2 certain;
but the converse does not hold:

Order is Important

Changing the order

$$q_2 = \exists x \exists y (T(\underline{y}, 60K) \land R(\underline{\text{Mary}, x}, y))$$

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but the converse does not hold:

T	*Dname*	*Budget*
	R&D	60K
	MIS	60K

R	*FN*	*LN*	*Dname*
	Mary	Smith	R&D
	Mary	Smith	MIS

q_2 certain
φ_2' false

Determining the Order

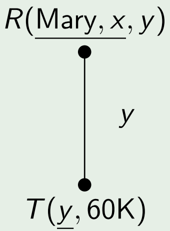
Attack graph

For each Boolean acyclic conjunctive query q, without self-join, we compute a directed graph, called attack graph:

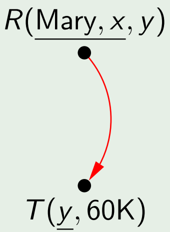
- The vertices are the atoms of q.
- The directed edges, to be defined later on, are such that a first-order expression for CERTAINTY(q) can be obtained by applying our "$\exists\forall$-rewrite function" on any topological sort of the attack graph.

Getting the Idea

Join tree



Attack graph



Functional Dependencies Implied by Primary Keys

Definition

We write vars($\vec{x}$) for the set of variables occurring in $\vec{x}$.

For single atom $F = R(\underline{\vec{x}}, \vec{y})$:

$$\mathcal{K}(F) := \text{vars}(\vec{x}) \rightarrow \text{vars}(\vec{x}\vec{y})$$

Extension to conjunctive query q:

$$\mathcal{K}(q) := \{\mathcal{K}(F) \mid F \text{ atom of } q\}$$

Example

$$\begin{aligned} q_2 &= \exists x \exists y (R(\underline{\text{Mary}, x}, y) \wedge T(\underline{y}, 60\text{K})) \\ \mathcal{K}(q_2) &= \{x \rightarrow xy, y \rightarrow y\} \end{aligned}$$

Attack Graph of a Join Tree

Attack graph

The attack graph of join tree τ contains a directed edge from $R(\underline{\vec{x}}, \vec{y})$ to another atom F if for each label L on the path that links $R(\underline{\vec{x}}, \vec{y})$ and F in τ:

$$\mathcal{K}(q \setminus \{R(\underline{\vec{x}}, \vec{y})\}) \not\models \mathrm{vars}(\vec{x}) \rightarrow L$$

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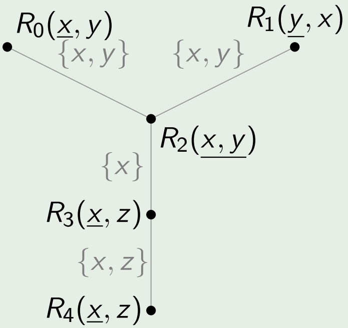

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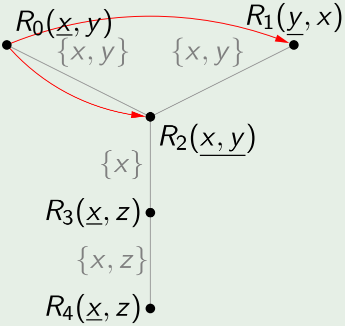

$$\mathcal{K}(q \setminus \{R_0(\underline{x}, y)\}) \equiv \{y \rightarrow x, x \rightarrow z\} \models x \rightarrow xz$$

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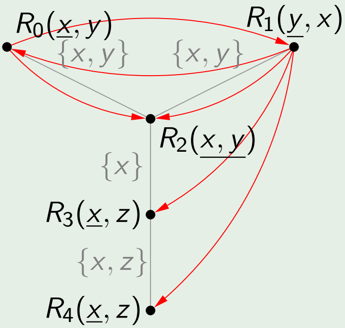

$$\mathcal{K}(q \setminus \{R_1(\underline{y}, x)\}) \equiv \{x \rightarrow y, x \rightarrow z\} \models y \rightarrow y$$

Attack Graph of a Join Tree

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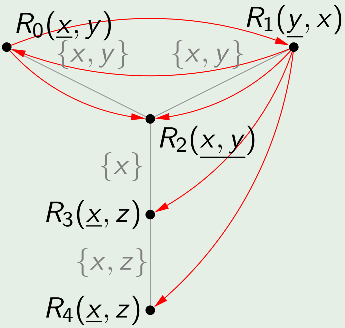

$$\mathcal{K}(q \setminus \{R_3(\underline{x}, z)\}) \equiv \{x \rightarrow y, y \rightarrow x, x \rightarrow z\} \models x \rightarrow xyz$$

Main Result

Acyclicity of attack graph is both sufficient and necessary for first-order expressibility.

Theorem

Let q be a Boolean conjunctive query, without self join.
Let τ be a join tree for q.

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Necessary If the attack graph of τ is cyclic, then CERTAINTY(q) is not first-order expressible.

Proof of Inexpressibility Result

Lemma

Let q be a Boolean conjunctive query, without self join.
Let τ be a join tree for q.
If the attack graph of τ is cyclic, then it has a cycle of size 2.

Then we can assume two distinct atoms, say F and G, such that the attack graph contains a directed edge from F to G, and a directed edge from G to F.

Two Databases that Locally Look the Same

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Our results apply to nonBoolean queries: treat free variables as new constants.

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Our results apply to nonBoolean queries: treat free variables as new constants.

NonBoolean query

$$q_2(v) \;=\; \exists x \exists y (R(\underline{\mathrm{Mary}, x}, y) \wedge T(\underline{y}, v))$$

$$\begin{aligned}\varphi_2(v) = \exists x \exists y \Big[& R(\underline{\mathrm{Mary}, x}, y) \wedge \\ & \forall y \Big(R(\underline{\mathrm{Mary}, x}, y) \rightarrow \big[\, T(\underline{y}, v) \wedge \\ & \qquad \forall z (\, T(\underline{y}, z) \rightarrow z = v)\big]\Big)\Big]\end{aligned}$$

For every unordered database, for every constant a,
$q_2(a)$ certain $\iff$ $\varphi_2(a)$ true.

Self-join

Acyclic conjunctive queries with self-join

$$
\begin{aligned}
q_4 &= \exists x \exists y \exists z(T(\underline{x}, y) \wedge T(\underline{y}, z)) \\
q_5 &= \exists x \exists y(T(\underline{x}, y) \wedge T(\underline{y}, c))
\end{aligned}
$$

We know from earlier work [Wij09]:

- CERTAINTY(q_4) is first-order expressible;
- CERTAINTY(q_5) is not first-order expressible.

Attack graphs cannot distinguish q_4 and q_5.

Cyclic Queries

Cyclic conjunctive query without self-join

Deciding first-order expressibility of CERTAINTY(q) for cyclic q remains open. For example,

$$q_6 = \exists x \exists y \exists z (R_0(\underline{x}, y), R_1(\underline{y}, z), R_2(\underline{z}, x))$$

It is not known whether CERTAINTY(q_6) is tractable.

Tractability of CERTAINTY(q)

For q ranging over the class of Boolean acyclic conjunctive queries without self-join:

- we can decide whether CERTAINTY(q) is first-order expressible (and hence in $\mathbf{AC}^0$);
- but can we decide whether CERTAINTY(q) is in **P**?

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Boundaries do not coincide

There exists q such that CERTAINTY(q) is in $\mathbf{P}$ but not first-order expressible [Wij10b].

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Dichotomy conjecture

CERTAINTY(q) is in **P** or is **coNP**-complete.

For queries with exactly 2 atoms, this dichotomy has recently been proved by Kolaitis and Pena.

The Counting Problem $\natural$CERTAINTY(q)

Definition

For a fixed Boolean query q, the problem $\natural$CERTAINTY(q) is:

Given an unordered database,

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Example

R	$\underline{FN}$	$\underline{LN}$	$Dname$
	Mary	Smith	R&D
	Mary	Smith	MIS
	Mary	Smith	Toys

T	$\underline{Dname}$	$Budget$
	R&D	60K
	MIS	60K
	Toys	60K
	Toys	70K

$$q_2 \quad = \quad \exists x \exists y (R(\underline{\text{Mary}, x}, y) \wedge T(\underline{y}, 60\text{K}))$$

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Complexity Dichotomy for $\natural$CERTAINTY(q)

Dichotomy [MW11]

For every Boolean conjunctive query q without self-join, at least one of the following holds:

- $\natural$CERTAINTY(q) is in **P**; or
- $\natural$CERTAINTY(q) is $\natural$**P**-complete under polynomial-time Turing reductions.

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Other dichotomy

A similar dichotomy holds in probabilistic databases [DRS11].

Summary of Main Results

- Uncertainty about currency leads to high data complexity. There exist conjunctive queries q, q' and sets Σ, Σ' of denials such that:
  - CERTAINTY(q) is **coNP**-hard
  - CONSISTENCY(Σ) is **NP**-hard
  - CPP(q', Σ'), certainty preservation under copying, is Σ_2^p-hard
- But:
  - For acyclic conjunctive queries q without self-join, we can decide whether CERTAINTY(q) is first-order definable (and hence in $\mathbf{AC}^0$).
  - For conjunctive queries q without self-join, we can decide whether $\natural$CERTAINTY(q) is in **P**.

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