Consistent Query Answering: Five Easy Pieces

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Inconsistent Databases

Database instance D:

- a finite first-order structure
- the information about the world

Integrity constraints IC:

- first-order logic formulas
- the properties of the world

Satisfaction of constraints: $D \models IC$

Formula satisfaction in a first-order structure.

Inconsistent database: $D \not\models IC$

Name	City	Salary
Gates	Redmond	20M
Gates	Redmond	30M
Grove	Santa Clara	10M

Name $\rightarrow$ City Salary

Whence Inconsistency?

Sources of inconsistency:

- integration of independent data sources with overlapping data
- time lag of updates (eventual consistency)
- unenforced integrity constraints
- dataspace systems,...

Eliminating inconsistency?

- not enough information, time, or money
- difficult, impossible or undesirable
- unnecessary: queries may be insensitive to inconsistency

Ignoring Inconsistency

Query results not reliable.

Name	City	Salary
Gates	Redmond	20M
Gates	Redmond	30M
Grove	Santa Clara	10M

Name $\rightarrow$ City Salary

SELECT Name
FROM Employee
WHERE Salary $\leq$ 25M

$\longrightarrow$

Name
Gates
Grove

Horizontal Decomposition

Decomposition into two relations:

- violators
- the rest

[Paredaens, De Bra: 1981–83]

Name	City	Salary
Gates	Redmond	20M
Gates	Redmond	30M
Grove	Santa Clara	10M

Name → City Salary

→

Grove	Santa Clara	10M

Name → City Salary

Gates	Redmond	20M
Gates	Redmond	30M

Name → City Salary

Exceptions to Constraints

Weakening the contraints:

- functional dependencies → denial constraints

[Borgida: TODS'85]

Name	City	Salary
Gates	Redmond	20M
Gates	Redmond	30M
Grove	Santa Clara	10M

Name → City Salary

→

Name	City	Salary
Gates	Redmond	20M
Gates	Redmond	30M
Grove	Santa Clara	10M

Name → City Salary

except Name='Gates'

The Impact of Inconsistency on Queries

Traditional view

- query results defined irrespective of integrity constraints
- query evaluation may be optimized in the presence of integrity constraints (semantic query optimization)

"Post-modernist" view

- inconsistency reflects uncertainty
- query results may depend on integrity constraint satisfaction
- inconsistency may be eliminated or tolerated

Database Repairs

Restoring consistency:

- insertion, deletion, update
- minimal change?

Name	City	Salary
Gates	Redmond	20M
Gates	Redmond	30M
Grove	Santa Clara	10M

Name $\rightarrow$ City Salary

Name	City	Salary
Gates	Redmond	30M
Grove	Santa Clara	10M

Name $\rightarrow$ City Salary

Name	City	Salary
Gates	Redmond	20M
Grove	Santa Clara	10M

Name $\rightarrow$ City Salary

Consistent query answer:

Query answer obtained in every repair.

[Arenas,Bertossi,Ch.: PODS'99]

Name	City	Salary
Gates	Redmond	20M
Gates	Redmond	30M
Grove	Santa Clara	10M

Name → City Salary

```
SELECT Name
FROM Employee
WHERE Salary ≥ 15M / ≤ 20M
```

Name
Gates
Grove

Research Goals

Formal definition

What constitutes reliable (consistent) information in an inconsistent database.

Algorithms

How to compute consistent information.

Computational complexity analysis

- tractable vs. intractable classes of queries and integrity constraints
- tradeoffs: complexity vs. expressiveness.

Implementation

- preferably using DBMS technology.

Applications

???

Basic Notions

Repair D' of a database D w.r.t. the integrity constraints IC:

- D': over the same schema as D
- $D' \models IC$
- symmetric difference between D and D' is minimal.

Consistent query answer to a query Q in D w.r.t. IC:

- an element of the result of Q in every repair of D w.r.t. IC.

Another incarnation of the idea of sure query answers
[Lipski: TODS'79].

A Logical Aside

Belief revision

- semantically: repairing $\equiv$ revising the database with integrity constraints
- consistent query answers $\equiv$ counterfactual inference.

Logical inconsistency

- inconsistent database: database facts together with integrity constraints form an inconsistent set of formulas
- trivialization of reasoning does not occur because constraints are not used in relational query evaluation.

Exponentially many repairs

Example relation $R(A, B)$

- violates the dependency $A \rightarrow B$
- has 2^n repairs.

A	B
a_1	b_1
a_1	c_1
a_2	b_2
a_2	c_2
...	
a_n	b_n
a_n	c_n

$A \rightarrow B$

It is impractical to apply the definition of CQA directly.

Computing Consistent Query Answers

Query Rewriting

Given a query Q and a set of integrity constraints IC, build a query Q^{IC} such that for every database instance D

> *the set of answers to* Q^{IC} *in* D = *the set of consistent answers to* Q *in* D *w.r.t.* IC.

Representing all repairs

Given IC and D:

1. build a space-efficient representation of all repairs of D w.r.t. IC
2. use this representation to answer (many) queries.

Logic programs

Given IC, D and Q:

1. build a logic program $P_{IC,D}$ whose models are the repairs of D w.r.t. IC
2. build a logic program P_Q expressing Q
3. use a logic programming system that computes the query atoms present in all models of $P_{IC,D} \cup P_Q$.

Constraint classes

Universal constraints

$\forall.\ \neg A_1 \vee \cdots \vee \neg A_n \vee B_1 \vee \cdots \vee B_m$

Example

$\forall.\ \neg Par(x) \vee Ma(x) \vee Fa(x)$

Denial constraints

$\forall.\ \neg A_1 \vee \cdots \vee \neg A_n$

Example

$\forall.\ \neg M(n, s, m) \vee \neg M(m, t, w) \vee s \leq t$

Functional dependencies

$X \rightarrow Y$:

- a key dependency in F if X is a key
- a primary-key dependency: only one key exists

Example primary-key dependency

Name $\rightarrow$ Address Salary

Inclusion dependencies

$R[X] \subseteq S[Y]$:

- a foreign key constraint if Y is a key of S

Example foreign key constraint

$M[Manager] \subseteq M[Name]$

Query Rewriting

Building queries that compute CQAs

- relational calculus (algebra) $\rightsquigarrow$ relational calculus (algebra)
- SQL $\rightsquigarrow$ SQL
- leads to PTIME data complexity

Query

$Emp(x, y, z)$

Query

$Emp(x, y, z)$

Integrity constraint

$\forall\ x, y, z, y', z'.\ \neg Emp(x, y, z) \vee \neg Emp(x, y', z') \vee z = z'$

Integrity constraint

$\forall\ x, y, z, y', z'.\ \neg Emp(x, y, z) \vee \neg Emp(x, y', z') \vee z = z'$

Rewritten query

$Emp(x, y, z) \wedge \forall\ y', z'.\ \neg Emp(x, y', z') \vee z = z'$

The Scope of Query Rewriting

[Arenas, Bertossi, Ch.: PODS'99]

- Queries: conjunctions of literals (relational algebra: $\sigma, \times, -$)
- Integrity constraints: binary universal

[Fuxman, Miller: ICDT'05]

- Queries: C_{forest}
  - a class of conjunctive queries ($\pi, \sigma, \times$)
  - no non-key or non-full joins
  - no repeated relation symbols
  - no built-ins
- Integrity constraints: primary key functional dependencies

SQL Rewriting

SQL query

```
SELECT Name FROM Emp
WHERE Salary ≥ 10K
```

SQL rewritten query

```
SELECT e1.Name FROM Emp e1
WHERE e1.Salary ≥ 10K AND NOT EXISTS
       (SELECT * FROM EMPLOYEE e2
       WHERE e2.Name = e1.Name AND e2.Salary < 10K)
```

[Fuxman, Fazli, Miller: SIGMOD'05]

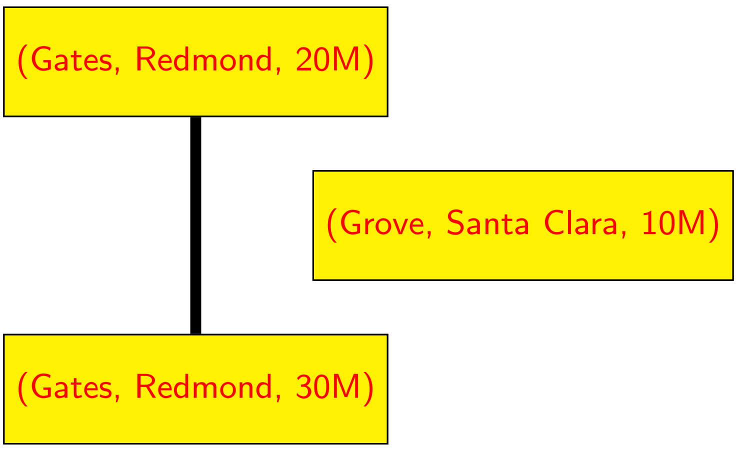
- ConQuer: a system for computing CQAs
- conjunctive (C_{forest}) and aggregation SQL queries
- databases can be annotated with consistency indicators
- tested on TPC-H queries and medium-size databases

Conflict Hypergraph

Vertices
Tuples in the database.

Edges
Minimal sets of tuples violating a constraint.

Repairs
Maximal independent sets in the conflict graph.



Computing CQAs Using Conflict Hypergraphs

Algorithm HProver

INPUT: query Φ a disjunction of ground atoms, conflict hypergraph G
OUTPUT: is Φ false in some repair of D w.r.t. IC?
ALGORITHM:

1. $\neg\Phi = P_1(t_1) \wedge \cdots \wedge P_m(t_m) \wedge \neg P_{m+1}(t_{m+1}) \wedge \cdots \wedge \neg P_n(t_n)$
2. find a consistent set of facts S such that
   - $S \supseteq \{P_1(t_1), \ldots, P_m(t_m)\}$
   - for every fact $A \in \{P_{m+1}(t_{m+1}), \ldots, P_n(t_n)\}$: $A \not\in D$ or there is an edge $E = \{A, B_1, \ldots, B_m\}$ in G and $S \supseteq \{B_1, \ldots, B_m\}$.

[Ch., Marcinkowski, Staworko: CIKM'04]

- Hippo: a system for computing CQAs in PTIME
- quantifier-free queries and denial constraints
- only edges of the conflict hypergraph are kept in main memory
- optimization can eliminate many (sometimes all) database accesses in HProver
- tested for medium-size synthetic databases

Logic programs

Specifying repairs as answer sets of logic programs

- [Arenas, Bertossi, Ch.: FQAS'00, TPLP'03]
- [Greco, Greco, Zumpano: LPAR'00, TKDE'03]
- [Calì, Lembo, Rosati: IJCAI'03]

Example

$emp(x, y, z) \leftarrow emp_D(x, y, z), not\ dubious\_emp(x, y, z).$
$dubious\_emp(x, y, z) \leftarrow emp_D(x, y, z), emp(x, y', z'), y \neq y'.$
$dubious\_emp(x, y, z) \leftarrow emp_D(x, y, z), emp(x, y', z'), z \neq z'.$

Answer sets

- $\{emp(Gates, Redmond, 20M), emp(Grove, SantaClara, 10M), \ldots\}$
- $\{emp(Gates, Redmond, 30M), emp(Grove, SantaClara, 10M), \ldots\}$

Logic Programs for computing CQAs

Logic Programs

- disjunction and classical negation
- checking whether an atom is in all answer sets is Π_2^p-complete
- `dlv`, `smodels`, ...

Scope

- arbitrary first-order queries
- universal constraints
- approach unlikely to yield tractable cases

INFOMIX [Eiter et al.: ICLP'03]

- combines CQA with data integration (GAV)
- uses `dlv` for repair computations
- optimization techniques: localization, factorization
- tested on small-to-medium-size legacy databases

Co-NP-completeness of CQA

Theorem (Ch., Marcinkowski: Inf. Comp.'05)

For primary-key functional dependencies and conjunctive queries, consistent query answering is data-complete for co-NP.

Proof.

Membership: V is a repair iff $V \models IC$ and $W \not\models IC$ if $W = V \cup M$.
Co-NP-hardness: reduction from MONOTONE 3-SAT.

1. Positive clauses $\beta_1 = \phi_1 \wedge \cdots \wedge \phi_m$, negative clauses $\beta_2 = \psi_{m+1} \wedge \cdots \wedge \psi_l$.
2. Database D contains two binary relations $R(A, B)$ and $S(A, B)$:
   - $R(i, p)$ if variable p occurs in ϕ_i, $i = 1, \ldots, m$.
   - $S(i, p)$ if variable p occurs in ψ_i, $i = m+1, \ldots, l$.
3. A is the primary key of both R and S.
4. Query $Q \equiv \exists x, y, z.\ \big(R(x, y) \wedge S(z, y)\big)$.
5. There is an assignment which satisfies $\beta_1 \wedge \beta_2$ iff there exists a repair in which Q is false.

□

Q does not belong to C_{forest}.

Data complexity of CQA

	Primary keys	*Arbitrary keys*	*Denial*	*Universal*
$\sigma, \times, -$	PTIME	PTIME	PTIME	PTIME: binary Π_2^p-complete
$\sigma, \times, -, \cup$	PTIME	PTIME	PTIME	Π_2^p-complete
σ, π	PTIME	co-NPC	co-NPC	Π_2^p-complete
$\sigma, \pi, \times$	co-NPC PTIME: C_{forest}	co-NPC	co-NPC	Π_2^p-complete
$\sigma, \pi, \times, -, \cup$	co-NPC	co-NPC	co-NPC	Π_2^p-complete

- [Arenas, Bertossi, Ch.: PODS'99]
- [Ch., Marcinkowski: Inf.Comp.'05]
- [Fuxman, Miller: ICDT'05]
- [Staworko, Ph.D.]

The Semantic Explosion

Tuple-based repairs

- asymmetric treatment of insertion and deletion:
  - repairs by minimal deletions only [Ch., Marcinkowski: Inf.Comp.'05]: data possibly incorrect but complete
  - repairs by minimal deletions and arbitrary insertions [Calì, Lembo, Rosati: PODS'03]: data possibly incorrect and incomplete
- minimal cardinality changes [Lopatenko, Bertossi: ICDT'07]

Attribute-based repairs

- (A) ground and non-ground repairs [Wijsen: TODS'05]
- (B) project-join repairs [Wijsen: FQAS'06]
- (C) repairs minimizing Euclidean distance [Bertossi et al.: DBPL'05]
- (D) repairs of minimum cost [Bohannon et al.: SIGMOD'05].

Computational complexity

- (A) and (B): similar to tuple based repairs
- (C) and (D): checking existence of a repair of cost $< K$ NP-complete.

The Need for Attribute-based Repairing

Tuple-based repairing leads to information loss.

EmpDept

Name	*Dept*	*Location*
John	Sales	Buffalo
Mary	Sales	Toronto

Name $\rightarrow$ Dept

Dept $\rightarrow$ City

Name	*Dept*	*Location*
John	Sales	Buffalo

Name $\rightarrow$ Dept

Dept $\rightarrow$ City

Name	*Dept*	*Location*
Mary	Sales	Toronto

Name $\rightarrow$ Dept

Dept $\rightarrow$ City

Attribute-based Repairs through Tuple-based Repairs

Repair a lossless join decomposition.

The decomposition:

$$\pi_{Name,Dept}(EmpDept) \bowtie \pi_{Dept,Location}(EmpDept)$$

Name	*Dept*	*Location*
John	Sales	Buffalo
John	Sales	Toronto
Mary	Sales	Buffalo
Mary	Sales	Toronto

Name $\rightarrow$ Dept

Dept $\rightarrow$ City

Name	*Dept*	*Location*
John	Sales	Buffalo
Mary	Sales	Buffalo

Name $\rightarrow$ Dept

Dept $\rightarrow$ City

Name	*Dept*	*Location*
John	Sales	Toronto
Mary	Sales	Toronto

Name $\rightarrow$ Dept

Dept $\rightarrow$ City

Probabilistic framework for "dirty" databases

[Andritsos, Fuxman, Miller: ICDE'06]

- potential duplicates identified and grouped into clusters
- worlds ≈ repairs: one tuple from each cluster
- world probability: product of tuple probabilities
- clean answers: in the query result in some (supporting) world
- clean answer probability: sum of the probabilities of supporting worlds
    - consistent answer: clean answer with probability 1

Salaries with probabilities

EmpProb

Name	*Salary*	Prob
Gates	20M	0.7
Gates	30M	0.3
Grove	10M	0.5
Grove	20M	0.5

Name → Salary

Computing Clean Answers

SQL query

```
SELECT Name
FROM EmpProb e
WHERE e.Salary > 15M
```

SQL rewritten query

```
SELECT e.Name,SUM(e.Prob)
FROM EmpProb e
WHERE e.Salary > 15M
GROUP BY e.Name
```

EmpProb

Name	*Salary*	Prob
Gates	20M	0.7
Gates	30M	0.3
Grove	10M	0.5
Grove	20M	0.5

Name → Salary

```
SELECT e.Name,SUM(e.Prob)
FROM EmpProb e
WHERE e.Salary > 15M
GROUP BY e.Name
```

→

Name	Prob
Gates	1
Grove	0.5

Consistent Query Answering: Looking Back

PODS'99, June 1999

- Arenas, Bertossi, Ch.: "Consistent Query Answers in Inconsistent Databases."

Other concurrent events:

Taking Stock: Good News

Technology

- practical methods for CQA for a subset of SQL:
  - restricted conjunctive/aggregation queries, primary/foreign-key constraints
  - quantifier-free queries/denial constraints
  - LP-based approaches for expressive query/constraint languages
- implemented in prototype systems
- tested on medium-size databases

The CQA Community

- over 30 active researchers
- up to 100 publications (since 1999)
- outreach to the AI community (qualified success)

Taking Stock: Initial Progress

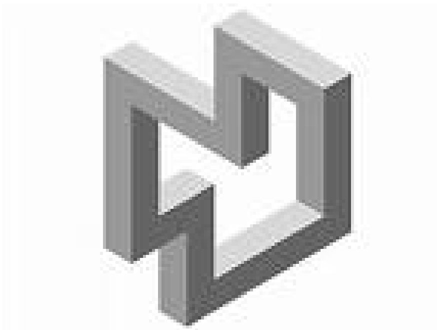
"Blending in" CQA

- data integration: tension between repairing and satisfying source-to-target dependencies
- peer-to-peer: how to isolate an inconsistent peer?

Extensions

- nulls:
  - repairs with nulls?
  - clean semantics vs. SQL conformance
- priorities:
  - preferred repairs
  - application: conflict resolution
- XML
  - notions of integrity constraint and repair
  - repair minimality based on tree edit distance?
- aggregate constraints

Taking Stock: Largely Open Issues



Applications

- no deployed applications
- repairing vs. CQA: data and query characteristics
- heuristics for CQA and repairing

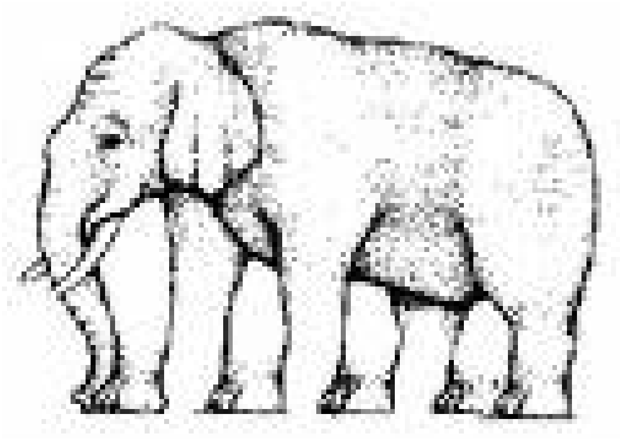
Consolidation

- taming the semantic explosion
- general first-order definability of CQA
- CQA and data cleaning
- CQA and schema matching/mapping

Foundations

- defining measures of consistency
- more refined complexity analysis
- dynamic aspects

Inconsistent elephant (by Oscar Reutersvärd)



Selected overview papers

L. Bertossi, J. Chomicki, Query Answering in Inconsistent Databases. In *Logics for Emerging Applications of Databases,* J. Chomicki, R. van der Meyden, G. Saake [eds.], Springer-Verlag, 2003.

J. Chomicki and J. Marcinkowski, On the Computational Complexity of Minimal-Change Integrity Maintenance in Relational Databases. In *Inconsistency Tolerance,* L. Bertossi, A. Hunter, T. Schaub, editors, Springer-Verlag, 2004.

L. Bertossi, Consistent Query Answering in Databases. SIGMOD Record, June 2006.