Database Consistency: Logic-Based Approaches

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April 27-28, 2007

Plan of the course

1. Integrity constraints (Chomicki)
2. Consistent query answers (Chomicki)
3. Conditional dependencies (Fan)
4. Integrity constraints for XML (Fan)

Part I

Integrity constraints

Outline of Part I

Integrity constraints (dependencies)

Database instance D:

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

Integrity constraints Σ:

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

Satisfaction of constraints: $D \models \Sigma$

Formula satisfaction in a first-order structure.

Consistent database: $D \models \Sigma$

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

Name $\rightarrow$ City Salary

Inconsistent database: $D \not\models \Sigma$

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

Name $\rightarrow$ City Salary

The need for integrity constraints

Roles of integrity constraints

- capture the semantics of data:
  - legal values of attributes
  - object identity
  - relationships, associations
- reduce data errors $\Rightarrow$ data quality
- help in database design
- help in query formulation
- (usually) no effect on query semantics but ...
- query evaluation and analysis are affected:
  - indexes, access paths
  - query containment and equivalence
  - semantic query optimization (SQO)

Examples

- key functional dependency: *"every employee has a single address and salary"*
- denial constraint: *"no employee can earn more than her manager"*
- foreign key constraint: *"every manager is an employee"*

Constraint enforcement

Enforced by application programs

- constraint checks inserted into code
- code duplication and increased application complexity
- error-prone: different applications can make different assumptions
- prevent system-level optimizations

Enforced by DBMS

- constraint checks performed by DBMS ("factored out")
- violating updates rolled back
- leads to application simplification and reduces errors
- enables query optimizations
- but ... integrity checks are expensive and inflexible

Not enforced

- data comes from multiple, independent sources
- long transactions with inconsistent intermediate states
- enforcement too expensive

Basic issues

Implication

Given a set of ICs Σ and an IC σ, does $D \models \Sigma$ imply $D \models \sigma$ for every database D?

Axiomatization

Can the notion of implication be "axiomatized"?

Inconsistent databases

1. How to construct a consistent database on the basis of an inconsistent one?
2. How to obtain information unaffected by inconsistency?

ICs in logical form

Atomic formulas

- relational (database) atoms $P(x_1, \ldots, x_k)$
- equality atoms $x_1 = x_2$
- no constants

General form

$$\forall x_1, \ldots x_k.\ A_1 \wedge \cdots \wedge A_n \Rightarrow \exists y_1, \ldots, y_l.\ B_1 \wedge \cdots \wedge B_m.$$

Subclasses

- full dependencies: no existential variables ($l = 0$)
- tuple-generating dependencies (TGDs): no equality atoms
- equality-generating dependencies (EGDs): $m = 1$, B_1 is an equality atom
- functional dependencies (FDs): typed binary unirelational EGDs
- join dependencies (JDs): TGDs with LHS a multiway join
- denial constraints: $l = 0$, $m = 0$
- inclusion dependencies (INDs): $n = m = 1$, no equality atoms

Examples

Database schema $NAM(Name, Address, Manager)$,
$NAS(Name, Address, Salary)$, $NM(Name, Manager)$.

Full TGD

$\forall n, a, m, s.\ NAS(n, a, s) \wedge NM(n, m) \Rightarrow NAM(n, a, m)$

Non-full TGD

$\forall n, a, m.\ NAM(n, a, m) \Rightarrow \exists s.\ NAS(n, a, s)$

Inclusion dependency (IND)

$NAM[Name, Address] \subseteq NAS[Name, Address]$

EGD

$\forall n, a, m, a', m'.\ NAM(n, a, m) \wedge NAM(n, a', m') \Rightarrow a = a'$

Functional dependency (FD)

$Name \rightarrow Address$

Implication: from linear-time to undecidable

Functional dependencies

1. view each attribute as a propositional variable
2. view each dependency $A_1 \dots A_k \to B \in \Sigma$ as a Horn clause $A_1 \wedge \dots \wedge A_k \Rightarrow B$
3. if $\sigma = C_1 \wedge \dots \wedge C_d \Rightarrow D$, then $\neg\sigma = C_1 \wedge \dots \wedge C_d \wedge \neg D$ consists of Horn clauses
4. thus $\Sigma \cup \neg\sigma$ is a set of Horn clauses whose (un)satisfiability can be tested in linear time (Dowling, Gallier [22])

Theorem (Chandra, Vardi [14])

The implication problem for functional dependencies together with inclusion dependencies is undecidable.

Implication in logic

No restriction to finite structures.

Finite and unrestricted implication

- coincide for full dependencies
- if they coincide, then they are decidable
- but not vice versa (FDs and unary INDs)

Counterexample

$\Sigma = \{A \to B, R[A] \subseteq R[B]\}$
$\sigma = R[B] \subseteq R[A]$

A	B
1	0
2	1
3	2
4	3
...	

Finite and unrestricted implication do not have to coincide.

Chase

Deciding the implication of full dependencies using chase

1. apply chase steps using the dependencies in Σ nondeterministically, obtaining a sequence of dependencies $\tau_0 = \sigma, \tau_1, \ldots, \tau_n$
2. stop when no chase steps can be applied to τ_n (a terminal chase sequence)
3. if τ_n is trivial, then Σ implies σ
4. otherwise, Σ does not imply σ

Trivial dependencies

- tgd: LHS contains RHS
- egd: RHS $\equiv x = x$

Fundamental properties of the chase

Terminal chase sequence $\tau_0 = \sigma, \tau_1, \ldots, \tau_n$:

- the LHS of τ_n, viewed as a database D_n, satisfies Σ
- if τ_n is nontrivial, then D_n violates σ
- the order of chase steps does not matter

Chase steps

A chase sequence $\tau_0 = \sigma, \tau_1, \ldots$.

Applying a chase step using a tgd C

1. view the LHS of τ_j as a database D_j
2. find a substitution h that (1) h makes the LHS of C true in D_j, and (2) h cannot be extended to a substitution that makes the RHS of C true in that instance
3. apply h to the RHS of C
4. add the resulting facts to the LHS of τ_j, obtaining τ_{j+1}

Applying a chase step using an egd C

1. view the LHS of τ_j as a database D_j
2. RHS of $C \equiv x_1 = x_2$
3. find a substitution h such that makes the LHS of C true in D_j and $h(x_1) \neq h(x_2)$
4. replace all the occurrences of $h(x_2)$ in τ_j by $h(x_1)$, obtaining τ_{j+1}

Chase in action

Integrity constraints

$C_1 = \forall x, y.\ P(x, y) \Rightarrow R(x, y)$
$C_2 = \forall x, y, z.\ R(x, y) \wedge R(x, z) \Rightarrow y = z$
$C_3 = \forall x, y, z.\ P(x, y) \wedge P(x, z) \Rightarrow y = z$

Goal

Show that $\{C_1, C_2\}$ implies C_3.

Terminal chase sequence

$\tau_0 = \{P(x, y) \wedge P(x, z) \Rightarrow y = z\}$
$\tau_1 = \{P(x, y) \wedge P(x, z) \wedge R(x, y) \Rightarrow y = z\}$
$\tau_2 = \{P(x, y) \wedge P(x, z) \wedge R(x, y) \wedge R(x, z) \Rightarrow y = z\}$
$\tau_3 = \{P(x, y) \wedge R(x, y) \Rightarrow y = y\}$: a trivial dependency

A general perspective

Computational complexity

Testing implication of full dependencies is:

- in EXPTIME (using chase)
- EXPTIME-complete (Chandra et al. [13])

First-order logic

- implication of σ by $\Sigma = \{\sigma_1, \ldots, \sigma_k\}$ is equivalent to the unsatisfiability of the formula $\Phi_{\Sigma,\sigma} \equiv \sigma_1 \wedge \cdots \wedge \sigma_k \wedge \neg\sigma$
- for full dependencies, the formulas $\Phi_{\Sigma,\sigma}$ are of the form $\exists^*\forall^*\phi$ where ϕ is quantifier-free (Bernays-Schöfinkel class)
- Bernays-Schöfinkel formulas have the finite-model property and their satisfiability is in NEXPTIME

Theorem proving

Chase corresponds to a combination of hyperresolution and paramodulation.

Axiomatization

Inference rules

- specific to classes of dependencies
- guarantee closure: only dependencies from the same class are derived
- bounded number of premises

Properties

Inference rules capture finite or unrestricted implication:

- soundness: all the dependencies derived from a given set Σ are implied by Σ
- completeness: all the dependencies implied by Σ can be derived from Σ
- finite set of rules $\Rightarrow$ implication decidable (but not vice versa)

Example axiomatization

Axiomatizing INDs

1. Reflexivity: $R[X] \subseteq R[X]$
2. Projection and permutation: If $R[A_1, \ldots A_m] \subseteq S[B_1, \ldots B_m]$, then $R[A_{i_1}, \ldots, A_{i_k}] \subseteq S[B_{i_1}, \ldots, B_{i_k}]$ for every sequence $i_1, \ldots, i_k$ of distinct integers in $\{1, \ldots, m\}$.
3. Transitivity: If $R[X] \subseteq S[Y]$ and $S[Y] \subseteq T[Z]$, then $R[X] \subseteq T[Z]$.

A derivation

Schemas $R(ABC)$ and $S(AB)$:

(1)	$S[AB] \subseteq R[AB]$	(given IND)
(2)	$R[C] \subseteq S[A]$	(given IND)
(3)	$S[A] \subseteq R[A]$	(from (1))
(4)	$R[C] \subseteq R[A]$	(from (2) and (3))

Review of results

	Implication	Axiomatization
FDs	PTIME	Finite
INDs	PSPACE-complete	Finite
FDs + INDs	Undecidable	No
Full (typed) dependencies	EXPTIME-complete	Yes
Join dependencies	NP-complete	No
First-order logic	Undecidable	Yes

Application: database design

Keys

A set of attributes $X \subseteq U$ is a key with respect to a set of FDs Σ if:

- Σ implies $X \rightarrow U$
- for no proper subset Y of X, Σ implies $Y \rightarrow U$

Decomposition

A decomposition $\mathcal{R} = (R_1, \ldots, R_n)$ of a schema R has the lossless join property with respect to a set of FDs Σ iff Σ implies the join dependency $\bowtie [\mathcal{R}]$.

Decomposition (R_1, R_2) of $R(ABC)$

Relation schemas: $R_1(AB)$ with FD $A \rightarrow B$, $R_2(AC)$.
Terminal chase sequence:

$R(x, y, z') \wedge R(x, y', z) \Rightarrow R(x, y, z)$ given JD

$R(x, y, z') \wedge R(x, y, z) \Rightarrow R(x, y, z)$ chase with $A \rightarrow B$

Application: data exchange

Goal

Exchange of data between independent databases with different schemas.

Setting for data exchange

- source and target schemas
- source-to-target dependencies : describe how the data is mapped between source and target
- target integrity constraints

Data exchange is a specific scenario for data integration, in which a target instance is constructed.

Constraints and solutions

ϕ_S, ϕ_T, ψ_T are conjunctions of relation atomic formulas over source and target.

Source-to-target dependencies Σ_{st}

- tuple-generating dependencies: $\forall \mathbf{x}\ (\phi_{\mathbf{S}}(\mathbf{x}) \Rightarrow \exists \mathbf{y}\ \psi_{\mathbf{T}}(\mathbf{x}, \mathbf{y}))$.

Target integrity constraints Σ_t

- tuple-generating dependencies (tgds): $\forall \mathbf{x}\ (\phi_{\mathbf{T}}(\mathbf{x}) \Rightarrow \exists \mathbf{y}\ \psi_{\mathbf{T}}(\mathbf{x}, \mathbf{y}))$
- equality-generating dependencies: $\forall \mathbf{x}\ (\phi_{\mathbf{T}}(\mathbf{x}) \Rightarrow \mathbf{x_1} = \mathbf{x_2})$.

Solution

Given a source instance I, a target instance J is

- a solution for I if J satisfies Σ_t and (I, J) satisfy Σ_{st}
- a universal solution for I if it is a solution for I and there is a homomorphism from it to any other solution for I
- solutions can contain labelled nulls

There may be multiple solutions.

Query evaluation (Fagin et al.[24])

Certain answer

Given a query Q and a source instance I, a tuple t is a certain answer with respect to I if t is an answer to Q in every solution J for I.

Conjunctive queries

- relational calculus: $\exists, \wedge$
- relational algebra: $\sigma, \pi, \times$

Query evaluation

1. construct any universal solution J_0
2. evaluate the query over J_0
3. discard answers with nulls
4. the above returns certain answers for unions of conjunctive queries without inequalities

Building a universal solution [24]

Apply a variant of the chase [1] to the source instance using target and source-to-target dependencies, obtaining a sequence of instances $I_0 = I, I_1, \ldots, I_n, \ldots$.

Chasing a tgd C

1. find a substitution h that (1) h makes the LHS of C true in the constructed instance I_j, and (2) h cannot be extended to a substitution that makes the RHS of C true in that instance
2. apply h to the RHS of C, mapping the existentially quantified variables to fresh labelled nulls
3. add the resulting facts to I_j, obtaining I_{j+1}.

Chasing an egd C

Find a substitution h such that makes the LHS of C true in I_j and $h(x_1) \neq h(x_2)$:

- if $h(x_1)$ and $h(x_2)$ are constants, then FAILURE
- otherwise, identify $h(x_1)$ and $h(x_2)$ in I_j (preferring constants), obtaining I_{j+1}.

Chase at work

Source and target databases

Source: $Emp(N, A)$, $Num(N, Id)$

Target: $Name(Id, N)$, $Addr(Id, A)$

Source-to-target dependencies

$\forall n, a.\ Emp(n, a) \Rightarrow \exists id.\ Name(id, n) \wedge Addr(id, a)$

$\forall n, a, id.\ Emp(n, a) \wedge Num(n, id) \Rightarrow Name(id, n)$

Target constraints

$Name: \ N \rightarrow Id, Id \rightarrow N,\ Addr: \ Id \rightarrow A.$

Chase sequence

$I_0 = \{Emp(Li, LA), Num(Li, 111)\}$

$I_1 = \{Emp(Li, LA), Num(Li, 111), Name(id_1, Li), Addr(id_1, LA)\}$

$I_2 = \{Emp(Li, LA), Num(Li, 111), Name(id_1, Li), Addr(id_1, LA), Name(111, Li)\}$

$I_3 = \{Emp(Li, LA), Num(Li, 111), Name(111, Li), Addr(111, LA)\}$

Chase termination

Chase result

- there is a sequence of chase applications that ends in failure: no universal solution
- otherwise: every finite sequence that cannot be extended yields a universal solution

Termination

For weakly acyclic tgds, each chase sequence is of length polynomial in the size of the input.

Data complexity of computing certain answers

- in PTIME for unions of conjunctive queries (without inequalities) and constraints that are egds and weakly acyclic tgds
- co-NP-complete for unions of conjunctive queries (with inequalities) and constraints that are egds and weakly acyclic tgds

Application: semantic query optimization

Query optimization

- rewrite-based
- cost-based

Semantic query optimization

Rewritings enabled by satisfaction of integrity constraints:

- join elimination/introduction
- predicate elimination/introduction
- eliminating redundancies
- ...

Preference queries

The winnow operator ω_C (Chomicki [15])

Find the best answers to a query, according to a given preference relation $\succ_C$.

Relation *Book(Title,Vendor,Price)*

$$\text{Preference: } (i, v, p) \succ_{C_1} (i', v', p') \equiv i = i' \wedge p < p'$$
$$\text{Indifference: } (i, v, p) \sim_{C_1} (i', v', p') \equiv i \neq i' \vee p = p'$$

Book	*Title*	*Vendor*	*Price*
t_1	The Flanders Panel	`amazon.com`	\$14.75
t_2	The Flanders Panel	`fatbrain.com`	\$13.50
t_3	The Flanders Panel	`bn.com`	\$18.80
t_4	Green Guide: Greece	`bn.com`	\$17.30

Book	*Title*	*Vendor*	*Price*
t_1	The Flanders Panel	`amazon.com`	\$14.75
t_2	The Flanders Panel	`fatbrain.com`	\$13.50

Eliminating redundant occurrences of winnow

Redundant winnow (Chomicki [17])

Given a set of integrity constraints Σ, $\omega_C(r) = r$ for every relation r satisfying Σ iff Σ implies the dependency

$$R(t_1) \wedge R(t_2) \Rightarrow t_1 \sim_C t_2.$$

Example

$$Book(i_1, v_1, p_1) \wedge Book(i_2, v_2, p_2) \Rightarrow i_1 \neq i_2 \vee p_1 = p_2$$

is a functional dependency in disguise:

$$Book(i_1, v_1, p_1) \wedge Book(i_2, v_2, p_2) \wedge i_1 = i_2 \Rightarrow p_1 = p_2.$$

If this dependency is implied by Σ, $\omega_C(Book) = Book$.

Constraint-generating dependencies (Baudinet et al. [5])

- general form:
  $\forall t_1, \ldots t_n.\ R(t_1) \wedge \cdots \wedge R(t_n) \wedge C(t_1, \ldots, t_n) \Rightarrow C_0(t_1, \ldots, t_n)$
- implication of CGDs is decidable for decidable constraint classes
- implication in PTIME for some classes of CGDs
- axiomatization not known

Prospects for integrity constraints

XML

- constraint classes
- normalization
- schema mapping
- equational chase

Semantic Web

- knowledge bases and ontologies
- extensions of ICs
- relational representations

Data mining

- discovery of FDs and INDs

Data cleaning

Part II

Consistent query answers

Outline of Part II

6 Motivation

7 Basics

8 Computing CQA
   - Methods
   - Complexity

9 Variants of CQA

10 Conclusions

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 ≤ 25M
```

Name
Gates
Grove

Horizontal Decomposition

Decomposition into two relations:

- violators
- the rest

(De Bra, Paredaens [21])

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

Name $\longrightarrow$ City Salary

Grove	Santa Clara	10M

Name $\longrightarrow$ City Salary

Gates	Redmond	20M
Gates	Redmond	30M

Name $\longrightarrow$ City Salary

Exceptions to Constraints

Weakening the contraints:

- functional dependencies $\longrightarrow$ denial constraints

(Borgida [10])

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

Name $\longrightarrow$ City Salary

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

Name $\longrightarrow$ 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)

Our 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 Answering

Consistent query answer:
Query answer obtained in every repair.

(Arenas, Bertossi, Chomicki [3])

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

Name → City Salary

SELECT Name
FROM Employee
WHERE Salary ≥ 10M

→

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

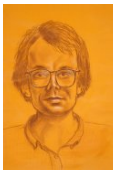
Repair D' of a database D w.r.t. the integrity constraints IC:

- 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 $Y = U$
- 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, Chomicki [3])

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

(Fuxman, Miller [26])

- 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 et al. [25])

- 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

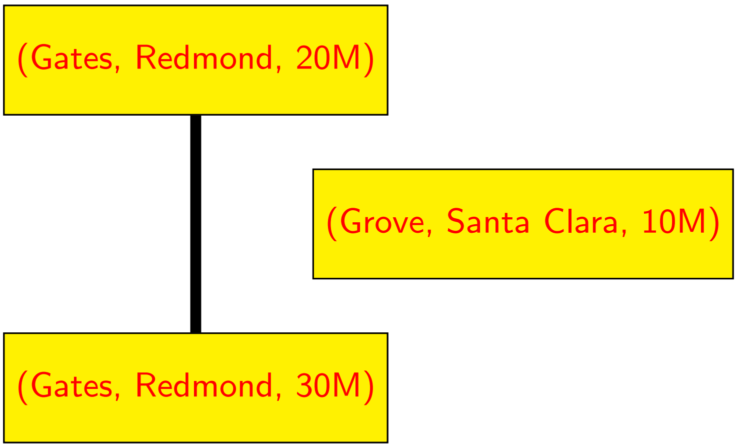
Tuples in the database.

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 $A \in \{P_{m+1}(t_{m+1}), \ldots, P_n(t_n)\}$: $A \notin D$ or there is an edge $E = \{A, B_1, \ldots, B_m\}$ in G and $S \supseteq \{B_1, \ldots, B_m\}$.

(Chomicki et al. [20])

- 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, Chomicki [4])
- (Greco, Greco, Zumpano [27])
- (Calì, Lembo, Rosati [12])

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. [23])

- 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 (Chomicki, Marcinkowski [19])

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

Proof.

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

1. Positive clauses $\beta_1 = \phi_1 \wedge \ldots \phi_m$, negative clauses $\beta_2 = \psi_{m+1} \ldots \wedge \psi_l$.
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.

$\square$

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^p_2-complete
$\sigma, \times, -, \cup$	PTIME	PTIME	PTIME	Π^p_2-complete
σ, π	PTIME	co-NPC	co-NPC	Π^p_2-complete
$\sigma, \pi, \times$	co-NPC PTIME: C_{forest}	co-NPC	co-NPC	Π^p_2-complete
$\sigma, \pi, \times, -, \cup$	co-NPC	co-NPC	co-NPC	Π^p_2-complete

- (Arenas, Bertossi, Chomicki [3])
- (Chomicki, Marcinkowski [19])
- (Fuxman, Miller [26])
- (Staworko, Ph.D., 2007)

The Semantic Explosion

Tuple-based repairs

- asymmetric treatment of insertion and deletion:
  - repairs by minimal deletions only (Chomicki, Marcinkowski [19]) data possibly incorrect but complete
  - repairs by minimal deletions and arbitrary insertions (Calì, Lembo, Rosati [11]) data possibly incorrect and incomplete
- minimal cardinality changes (Lopatenko, Bertossi [28])

Attribute-based repairs

- (A) ground and non-ground repairs (Wijsen [29])
- (B) project-join repairs (Wijsen [30])
- (C) repairs minimizing Euclidean distance (Bertossi et al. [7])
- (D) repairs of minimum cost (Bohannon et al. [9])

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 $\longrightarrow$ Dept

Dept $\longrightarrow$ City

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

Name $\longrightarrow$ Dept

Dept $\longrightarrow$ City

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

Name $\longrightarrow$ Dept

Dept $\longrightarrow$ City

Probabilistic framework for "dirty" databases

(Andritsos, Fuxman, Miller [2])

- potential duplicates identified and grouped into clusters
- worlds $\approx$ 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 $\longrightarrow$ 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 $\longrightarrow$ Salary

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

$\longrightarrow$

Name	Prob
Gates	1
Grove	0.5

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)
- overview papers [8, 6, 16, 18]

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?

Taking Stock: Largely Open Issues

Applications

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

CQA in context

- taming the semantic explosion
- CQA and data cleaning
- CQA and schema matching/mapping

Foundations

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

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