Database Consistency: Logic-Based Approaches

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Plan of the course

1. Integrity constraints

2. Consistent query answers

Part I

Integrity constraints

Outline of Part I

1. Basic notions
2. Implication of dependencies
3. Axiomatization
4. Applications
   - Database design
   - Data exchange
   - Semantic query optimization
5. Prospects

Integrity constraints (dependencies)

Database instance D:

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Gates	Redmond	30M
Grove	Santa Clara	10M

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

Name	City	Salary
Gates	Redmond	20M
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The need for integrity constraints

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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"*

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Roles of integrity constraints

- capture the semantics of data:
  - legal values of attributes
  - object identity
  - relationships, associations (in value-based data models)
- 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)
- specify database mappings

Constraint enforcement

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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

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- violating updates rolled back
- leads to application simplification and reduces errors
- enables query optimizations
- but ... integrity checks are expensive and inflexible

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Not enforced

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

Basic issues

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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

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Atomic formulas

- relational (database) atoms $P(x_1, \ldots, x_k)$ and equality atoms $x_1 = x_2$
- (usually) typed
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General form

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

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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): 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

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

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Full TGD

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

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Non-full (embedded) TGD

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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

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Functional dependencies

1. view each attribute as a propositional variable
2. view each dependency $A_1 \ldots A_k \rightarrow B \in \Sigma$ as a Horn clause $A_1 \wedge \cdots \wedge A_k \Rightarrow B$
3. if $\sigma = C_1 \wedge \cdots \wedge C_d \Rightarrow D$, then $\neg\sigma = C_1 \wedge \cdots \wedge C_d \wedge \neg D$ 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 [DG84])

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Theorem (Chandra, Vardi [CV85])

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

Implication in logic

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3	2
4	3

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

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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

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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
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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

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Integrity constraints

$C_1 = \forall x, y.\ P(x, y) \Rightarrow R(x, y)$
$C_2 = \forall x, y, z.\ R(x, y) \wedge R(x, z) \Rightarrow y = z$
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$\tau_3 = \{P(x,y) \wedge R(x,y) \Rightarrow y = y\}$: a trivial dependency

A general perspective

Computational complexity

Testing implication of full dependencies is:

- in EXPTIME (using chase)
- EXPTIME-complete (Chandra et al. [CLM81])

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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-Schönfinkel class)
- Bernays-Schönfinkel formulas have the finite-model property and their satisfiability is in NEXPTIME

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Theorem proving

Chase corresponds to a combination of hyperresolution and paramodulation.

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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

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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 $R[X] \subseteq T[Z]$.

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

(1) $S[AB] \subseteq R[AB]$ (given IND)

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(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	Yes
INDs	PSPACE-complete	Yes
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:

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

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Terminal chase sequence:

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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:

$$R(x,y,z') \wedge R(x,y',z) \Rightarrow R(x,y,z) \quad \text{given JD}$$

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 $Y \rightarrow U$

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Application: data exchange

Goal

Exchange of data between independent databases with different schemas.

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Setting for data exchange

- source and target schemas
- source-to-target dependencies : describe how the data is mapped between source and target
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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 relational atoms 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: $\forall \mathbf{x}\ (\phi_{\mathbf{T}}(\mathbf{x}) \Rightarrow \mathbf{x_1} = \mathbf{x_2})$.

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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

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There may be multiple solutions.

Query evaluation (Fagin et al.[FKMP05])

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.

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

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- 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 [FKMP05]

Apply a variant of the chase [AHV95] to the source instance using target and source-to-target dependencies, obtaining a sequence of instances $I_0 = I, I_1, \ldots, I_n, \ldots$.

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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
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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

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Source and target databases

Source: $Emp(N, A)$, $Num(N, Id)$ Target: $Name(Id, N)$, $Addr(Id, A)$

Chase at work

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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

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

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

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

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

Chase at work

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Source: $Emp(N, A)$, $Num(N, Id)$ Target: $Name(Id, N)$, $Addr(Id, A)$

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

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

Chase termination

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- there is a sequence of chase applications that ends in failure: no universal solution
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Termination

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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

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Query optimization

- rewrite-based
- cost-based

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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 [Cho03])

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

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Relation *Book(Title,Vendor,Price)*

Preference: $(i_1, v_1, p_1) \succ_{C_1} (i_2, v_2, p_2) \equiv i_1 = i_2 \wedge p_1 < p_2$

Indifference: $(i_1, v_1, p_1) \sim_{C_1} (i_2, v_2, p_2) \equiv i_1 \neq i_2 \vee p_1 = p_2$

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is a functional dependency in disguise:

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Constraint-generating dependencies (Baudinet et al. [BCW95])

- 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

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Schema mapping

- second-order dependencies to achieve closure under composition (Fagin et al. [FKPT05])

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- knowledge bases and ontologies
- extensions of ICs

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Semantic Web

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Data mining

- discovery of FDs and INDs

Part II

Consistent query answers

Outline of Part II

Whence Inconsistency?

Sources of inconsistency:

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

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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.

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Name	City	Salary
Gates	Redmond	20M
Gates	Redmond	30M
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Name $\longrightarrow$ City Salary

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

$\longrightarrow$

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Name
Gates
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Horizontal Decomposition

Decomposition into two relations:

- violators
- the rest

(De Bra, Paredaens [DBP83])

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Exceptions to Constraints

Weakening the contraints:

- functional dependencies $\longrightarrow$ denial constraints

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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)

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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
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Query answer obtained in every repair.

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Consistent Query Answering

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$\longrightarrow$

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Name	City	Salary
Gates	Redmond	20M
Gates	Redmond	30M
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Name → City Salary

```
SELECT Name
FROM Employee
WHERE Salary ≥ 10M
```

→

Name
Gates
Grove

Formal definition

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

Research Goals

Formal definition

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

Algorithms

How to compute consistent information.

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Computational complexity analysis

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

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- preferably using DBMS technology.

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Applications

???

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.

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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.

Example relation $R(A, B)$

- violates the dependency $A \longrightarrow B$
- 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

$A \longrightarrow B$

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$A \longrightarrow B$

It is impractical to apply the definition of CQA directly.

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

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Given IC and D:

1. build a space-efficient representation of all repairs of D w.r.t. IC
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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

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

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Example

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Example

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

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Functional dependencies

$X \rightarrow Y$:

- a key dependency in F if $Y = U$
- a primary-key dependency: only one key exists

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Example primary-key dependency

Name $\rightarrow$ Address Salary

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

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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

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

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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 [ABC99])

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

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(Fuxman, Miller [FM07])

- Integrity constraints: primary key functional dependencies
- 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
- Generalization: conjunctive queries expressed as rooted rules (Wijsen [Wij07])

SQL Rewriting

SQL query

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

(Fuxman, Fazli, Miller [FM05])

- 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.

(Gates, Redmond, 20M)

(Grove, Santa Clara, 10M)

(Gates, Redmond, 30M)

Conflict Hypergraph

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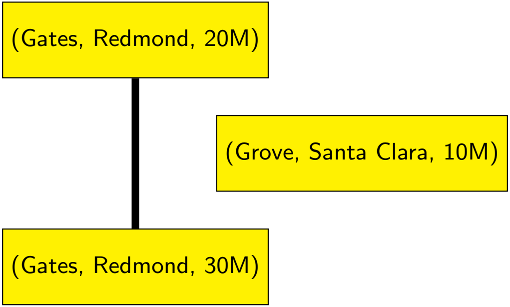
Tuples in the database.

Edges

Minimal sets of tuples violating a constraint.



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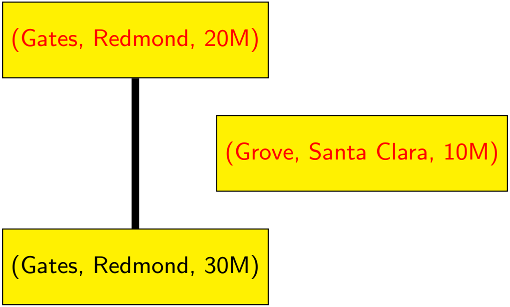

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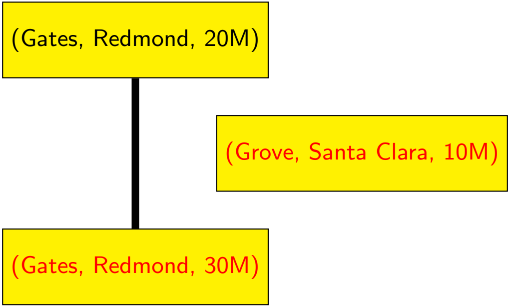

Algorithm HProver

INPUT: query Φ a disjunction of ground literals, 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 $S \supseteq \{B_1, \ldots, B_m\}$.

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(Chomicki, Marcinkowski, Staworko [CMS04])

- 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

Specifying repairs as answer sets of logic programs

- (Arenas, Bertossi, Chomicki [ABC03])
- (Greco, Greco, Zumpano [GGZ03])
- (Calì, Lembo, Rosati [CLR03b])

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Example

$emp(x, y, z) \leftarrow emp_D(x, y, z), not\ dubious\_emp(x, y, z).$
$dubious\_emp(x, y, z) \leftarrow emp_D(x, y, z), emp(x, y', z'), y \neq y'.$
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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
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- universal constraints
- approach unlikely to yield tractable cases

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INFOMIX (Eiter et al. [EFGL03])

- 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 [CM05a])

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

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Proof.

Membership: S is a repair iff $S \models IC$ and $W \not\models IC$ if $W = S \cup M$.
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 $Q \equiv \exists x, y, z. \left(R(x, y) \wedge S(z, y)\right)$.
5. There is an assignment which satisfies $\beta_1 \wedge \beta_2$ iff there exists a repair in which Q is false.

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□

Q does not belong to C_{forest}.

Data complexity of CQA

	Primary keys	*Arbitrary keys*	*Denial*	*Universal*
$\sigma, \times, -$				
$\sigma, \times, -, \cup$				
σ, π				
$\sigma, \pi, \times$				
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Data complexity of CQA

	Primary keys	*Arbitrary keys*	*Denial*	*Universal*
$\sigma, \times, -$	PTIME	PTIME		PTIME: binary
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$\sigma, \pi, \times$	co-NPC	co-NPC	co-NPC	
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- (Arenas, Bertossi, Chomicki [ABC99])
- (Chomicki, Marcinkowski [CM05a])
- (Fuxman, Miller [FM07])
- (Staworko, Ph.D., 2007):
  - co-NPC for full TGDs and denial constraints
  - PTIME for acyclic full TGDs and denial constraints

The Explosion of Semantics

Tuple-based repairs

- asymmetric treatment of insertion and deletion:
  - repairs by minimal deletions only (Chomicki, Marcinkowski [CM05a]): data possibly incorrect but complete
  - repairs by minimal deletions and arbitrary insertions (Calì, Lembo, Rosati [CLR03a]): data possibly incorrect and incomplete
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Attribute-based repairs

- (A) ground and non-ground repairs (Wijsen [Wij05])
- (B) project-join repairs (Wijsen [Wij06])
- (C) repairs minimizing Euclidean distance (Bertossi et al. [BBFL05])
- (D) repairs of minimum cost (Bohannon et al. [BFFR05])

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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.

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EmpDept

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

Name $\longrightarrow$ Dept

Dept $\longrightarrow$ City

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Attribute-based Repairs through Tuple-based Repairs (Wijsen [Wij06])

Repair the lossless join decomposition:

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

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Probabilistic framework for “dirty” databases

(Andritsos, Fuxman, Miller [AFM06])

- 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

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Salaries with probabilities

EmpProb

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

SQL query

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

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SELECT Name
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SQL rewritten query

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SELECT e.Name,SUM(e.Prob)
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Name → Salary

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→

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/acyclic TGDs/JDs
  - LP-based approaches for expressive query/constraint languages
- emergence of generic techniques
- implemented in prototype systems
- tested on medium-size databases

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/acyclic TGDs/JDs
  - LP-based approaches for expressive query/constraint languages
- emergence of generic techniques
- implemented in prototype systems
- tested on medium-size databases

The CQA Community

- over 30 active researchers
- over 100 publications (since 1999)
- overview papers [BC03, Ber06, Cho07a, CM05b]
- 2007 SIGMOD Doctoral Dissertation Award (Ariel Fuxman)

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?

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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

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Applications

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- repairing vs. CQA: data and query characteristics
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- CQA and data cleaning
- CQA and schema matching/mapping

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- repair checking
- defining measures of consistency
- more refined complexity analysis, dynamic aspects

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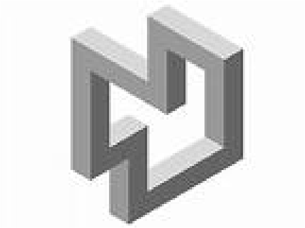

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