Managing Inconsistencies in Collaborative Data Management

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Structured Data

Public Sources

- Company Directories
- Product Catalogs
- Airline Schedules
- Weather Reports
- Patient Records
- Drug Studies

Enterprise Sources

- Personnel Records
- Equipment Databases
- Room Schedules
- Orders
- Inventories

Relationships Among Sources

Replicated data
- Cached data
- Materialized views (as in data warehouses)

Heterogeneity (different schemas or vocabularies)
- values in euros vs values in dollars
- French instead of English
- different numbers of tables or attributes

Real World Constraints
- Physical laws
- Governmental laws
- Business rules

Update

In the face of interrelationships among sources, updates to one source may necessitate updates to other sources in order to preserve their relationships.

Update Integration is the process of updating interrelated data sources in an integrated fashion. Analogous to **Data Integration** for data consumers.

Collaboration

In large enterprises, consortia, and open information systems (e.g. the WWW), it is common for different data sources to be controlled by different people. In such cases, the individuals performing updates must collaborate (explicitly or implicitly).

Collaborative Data Management (CDM) is update integration in a multiple user setting.

Inconsistencies

- In CDM, we capture the relationships between data sources as constraints written in a logical language
  - Not all relationships captured, but many important ones
- When multiple users update data sources independently, the constraints may be violated.
- We called these violations **inconsistencies**.

Inconsistency Management

- Identifying and indicating inconsistencies.
- Automatically updating some data sources to avoid inconsistencies.
- Answering queries in the presence of inconsistencies.

Decentralized Office assignment

- A building is divided into spaces.
- Each space as a “space czar” who is tasked with assigning people to offices within that space.
- The building manager, department manager, and department chair also exercise authority over the assignment of offices.
- Individual professors request specific assignments for his or her affiliates.

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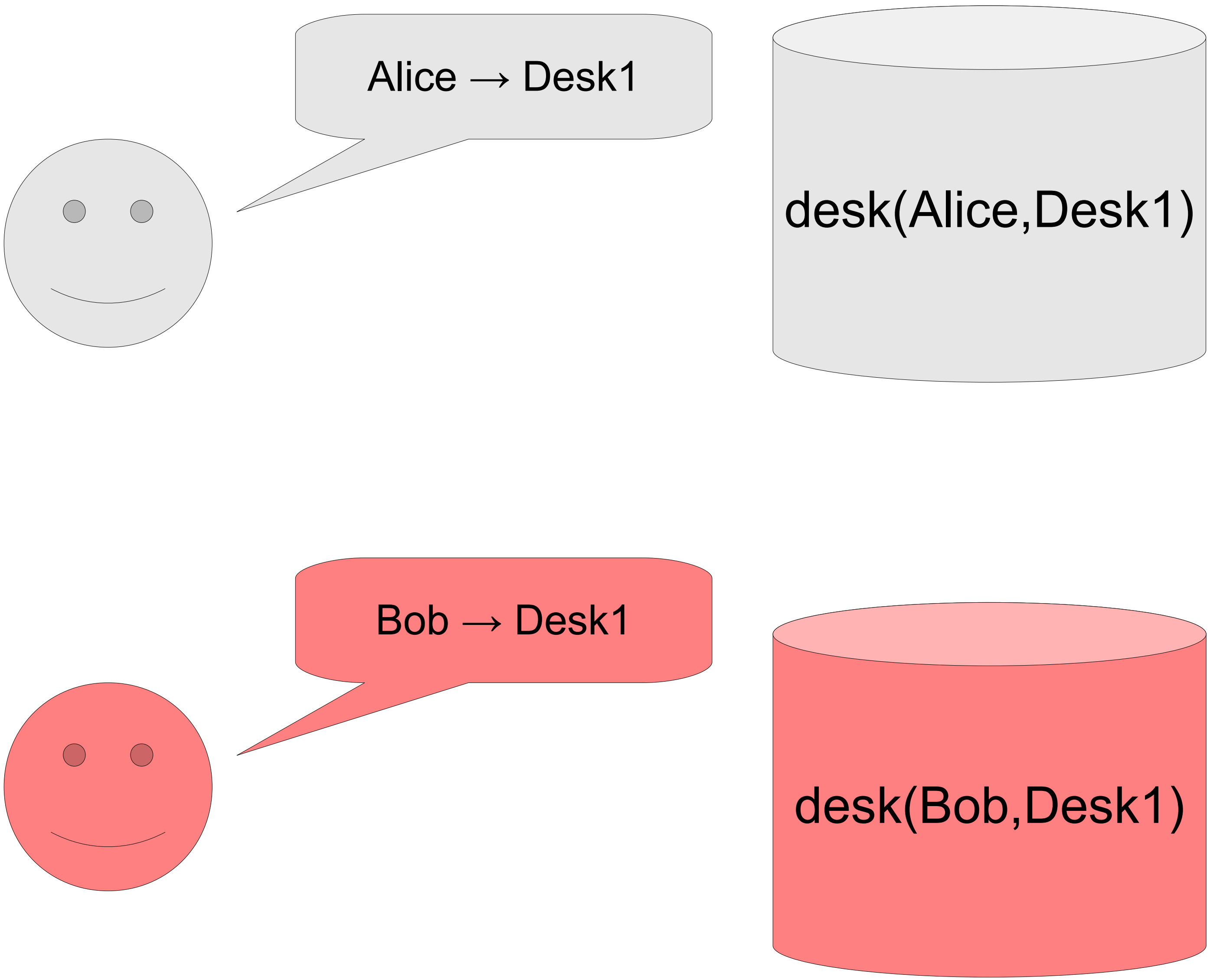
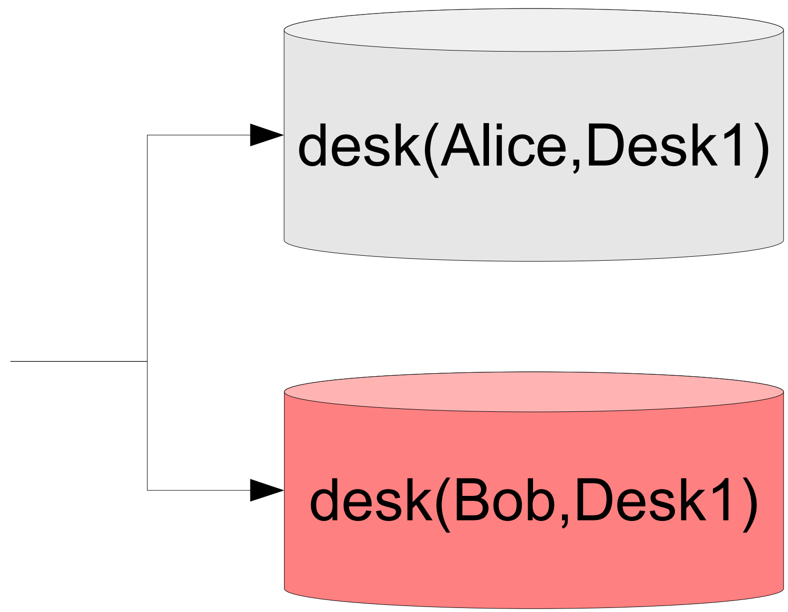
Desk Assignment Example



Desk Assignment Example

Conflict:
Data is inconsistent with the following constraint



$$\forall\ x1, x2, y$$
$$(\text{person.desk}(x1,y) \wedge \text{person.desk}(x2,y)$$
$$\rightarrow x1 = x2)$$

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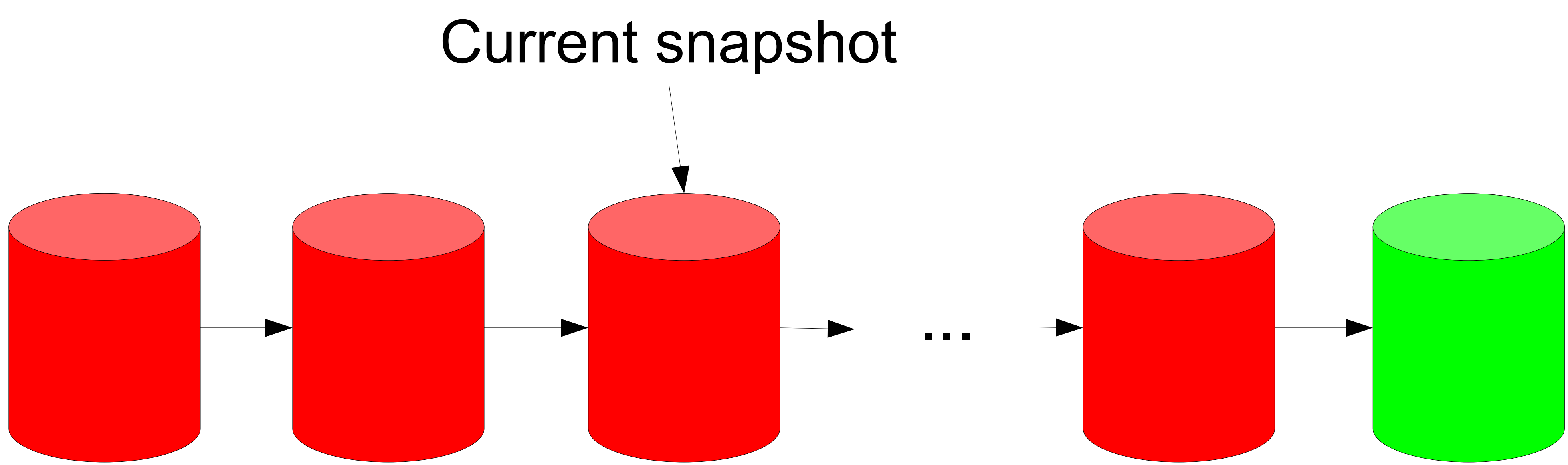
Alert the users to the conflict

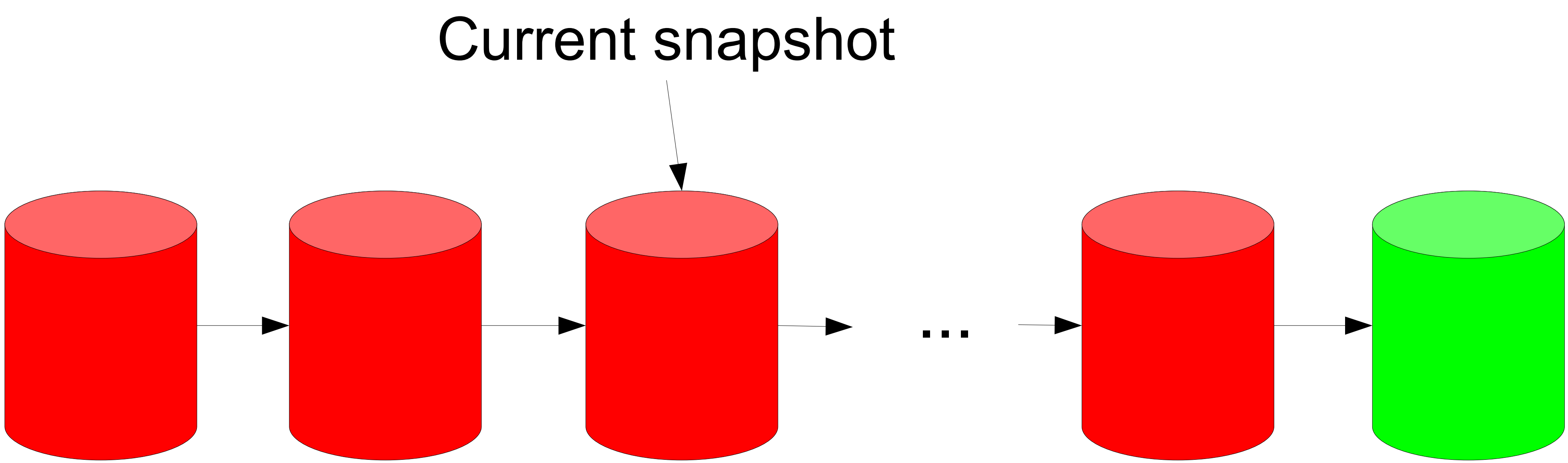
- The users can work to resolve the conflict

person.desk	
alice	desk1
bob	desk1
carol	desk2
david	desk3

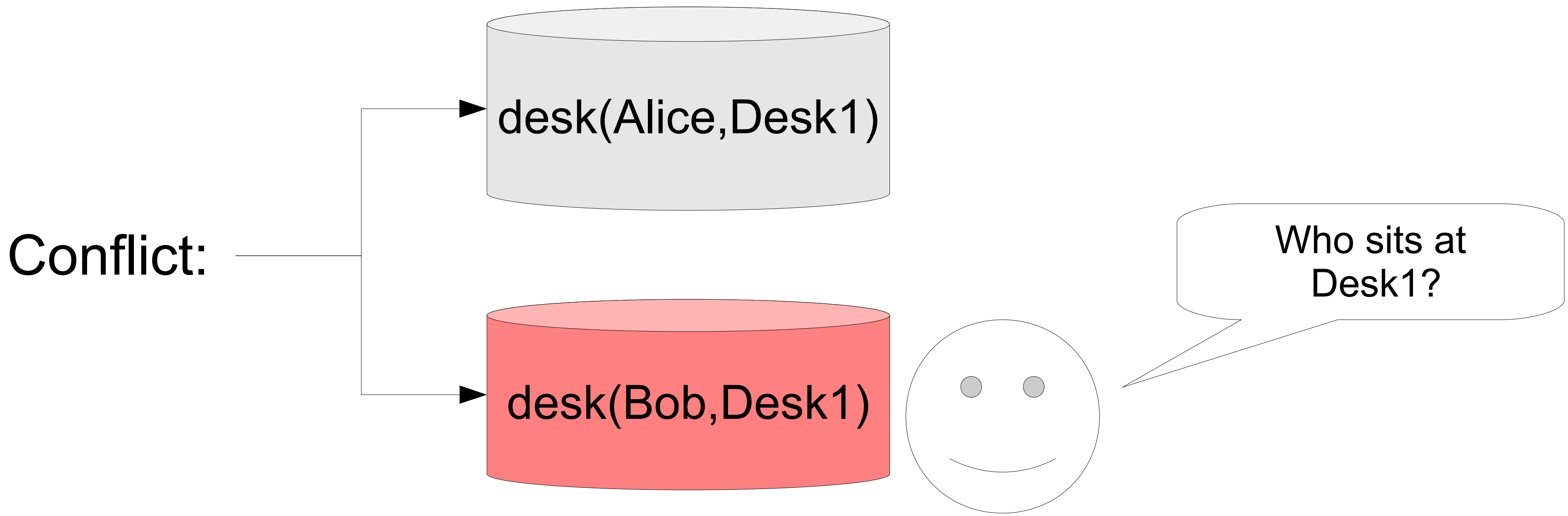


Queries

- Users would like to query the eventual, consistent data
- But all we have is the current, inconsistent, snapshot.



Queries



- Best guess: Alice or Bob, but not both!

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Relational Calculus Syntax

base formulas are atoms over S and equality (disequality) atoms of the form $e = e'(e \neq e')$ for terms e and e'. The well-formed formulas of the relational calculus over S include the base formulas and formulas of the form

1. $(\phi \wedge \psi)$, where ϕ and ψ are formulas over S;
2. $(\phi \vee \psi)$, where ϕ and ψ are formulas over S;
3. $\neg\phi$, where ϕ is a formula over S;
4. $\exists x \phi$, where x if a variable ϕ is a formula over S;
5. $\forall x \phi$, where x if a variable ϕ is a formula over S.

Database, Constraints

- Database instance
  A finite set of ground atoms
  - e.g., $D = \{\ p(a,a),\ p(b,c),\ q(a),\ r(a,d)\ \}$

- Constraint set
  A finite set of relational calculus sentences (no free variables)
  - e.g., $C = \{\ \forall x\, (\neg p(x,x) \vee q(x)),$
    $\exists x\, q(x)\ \}$

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Database Query

- Query
  A relational calculus formula
  - e.g., $Q_1 = p(a,b)$
  - e.g., $Q_2(x) = \exists y\ p(x,y)$
  - e.g., $Q_3(x) = \exists z \forall y\ (\neg p(x,y) \vee r(y,z))$

Min-change Repairs

- Given:
  - D : database — e.g., { p(a), p(b) }
  - Ω : set of constraints — e.g., $\{\neg p(a) \vee \neg p(b)\}$
- A repair is a database D* that is consistent with Ω.

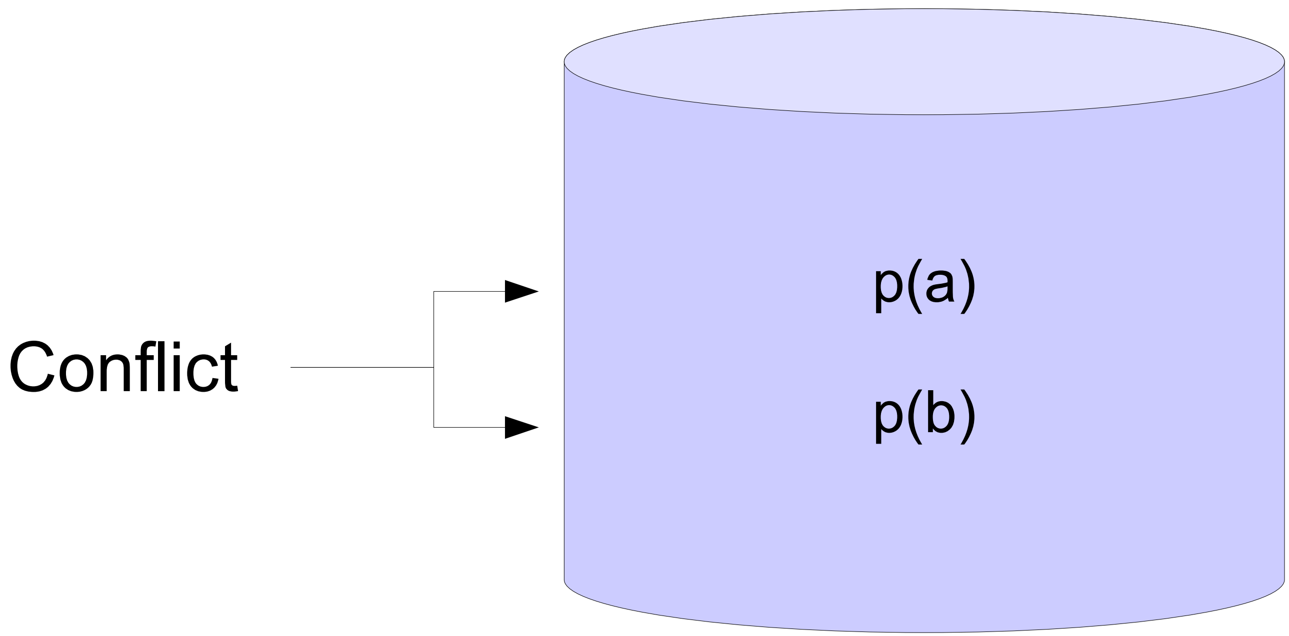
  e.g., { p(a) }, { p(b) }, { }, { p(a), p(c) }, ...
- A minimal change repair is a repair that is minimally different from D.

  e.g., { p(a) }, { p(b) }

Consistent query answers

- CQA: answers that arise no matter how the conflicts are resolved (in a minimal-change fashion) [ABC]
- $D \models^{CQA}_{\Omega} \; Q(t)$ iff
  for all minimal-change repairs D^* of D w.r.t. to Ω, $D^* \models Q(t)$

CQA



Constraint:
$\neg p(a) \lor \neg p(b)$

- p(a)? NO — {p(b)}
- p(b)? NO — {p(a)}
- $p(a) \land p(b)$? NO — {p(b)}
- $p(a) \lor p(b)$? YES — {p(a)}, {p(b)}

More lenient semantics

- In some situations, we would like to see plausible though non-guaranteed answers
  - e.g., a student checking out whom his office mates might be
- Possible answers from repairs: answers that arise from some minimal-change repair

Relax, not repair

- Constraint: every person must be assigned a desk
- Data: Charlie is missing a desk assignment
- Minimal-change repairs: {desk(Charles,desk1)}, {desk(Charles,desk2)}, {desk(Charles,desk3)}, …
- Possible answers: desk1, desk2, desk3, …

Incomplete Database

- An incomplete database is a pair $<P,N>$ where
  - P,N are sets of ground atoms
  - $P \cap N = \{\}$
- e.g., $K = <\{p(a),q(a)\},\ \{p(c),q(b)\}>$
- Intuitively,
  - P gives the known true atoms
  - N gives the known false atoms
  - The rest are unknown
- $<P,N> \vDash_{\mathbf{d}} Q$ iff $D \vDash_{\mathbf{d}} Q$ for all $D \in \text{Instances}_{\mathbf{d}}(<P,N>)$

Relaxations of a database

- A relaxation of D w.r.t. Ω is an incomplete database $K = \langle P,N \rangle$, where
  - $P,N \subseteq \text{base}(\mathbf{d})$
  - $P \subseteq D$
  - $N \cap D = \varnothing$
  - $\langle P,N \rangle \not\models_{\mathbf{d}} \neg\Omega$
- Let the set of relaxations of D w.r.t. to Ω be denoted $Re_{\mathbf{d}}(D,\Omega)$

Example

- $D = \{p(a), p(b)\}$
- $\Omega = \{\neg p(a) \vee \neg p(b)\}$
- $\mathbf{d} = \{a, b, c\}$
- $Re_{\mathbf{d}}(D, \Omega) = \{$

$$<\{p(a)\},\{p(c)\}>, \quad <\{p(b)\},\{p(c)\}>$$

$$<\{p(a)\},\{\}>, \quad <\{p(b)\},\{\}>$$

$$<\{\},\{p(c)\}>, \quad <\{\},\{\}> \quad \}$$

Answers with Consistent Support

- ACS: answers that are supported by a consistent relaxation of the database. [KG]
- $D \models^{CS}_{\Omega} Q(t)$ iff there exists $K \in Re_{\mathbf{d}}(D,\Omega)$ st $K \models_{\mathbf{d}} Q(t)$
  - Where $\mathbf{d} = \mathrm{adom}(D,Q)$

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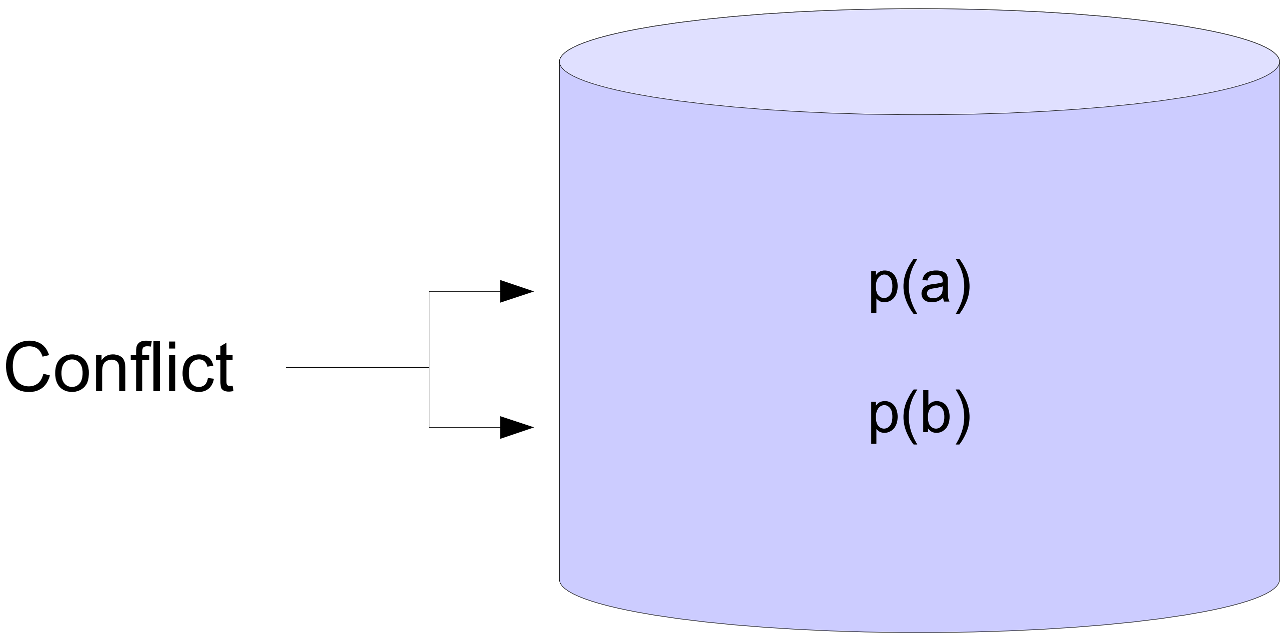
ACS



Constraint:
$\neg p(a) \vee \neg p(b)$

- p(a)? YES $<\{p(a)\},\{\}>$
- p(b)? YES $<\{p(b)\},\{\}>$
- p(a) $\wedge$ p(b)? NO
- p(a) $\vee$ p(b)? YES $<\{p(a)\},\{\}>$

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More complex queries

p	
a	1
b	1
c	2
d	3

q
a
b

r
c
d

Constraint:
$\forall xyz\ (\neg p(x,z) \lor \neg p(y,z) \lor x{=}y)$

- $\forall x\ [q(x) \rightarrow p(x,1)]$?
  - ACS: NO

Data Complexity

- Both ACS and CQA are NP-Hard problems [KG] [CM]
  - Reduction from monotone 3-SAT
- ACS is tractable for $\exists^*\forall^*$ queries†. [KG]
- CQA is tractable for
  - $\forall^*$ queries† [KG]
  - Some subclasses of $\exists^*$ queries† [ABC, CM, FM]

† with suitable restrictions on the class of constraints

Query rewriting

- How can we use existing database infrastructure to support these query semantics?

- Solution: Query rewriting
  - Algorithm ACS-Rewrite[Q,Ω]
    Rewrite Q ($\exists^*\forall^*$) into Q' so that evaluating Q' on a standard DBMS gives ACS answers to Q. [KG]
  - Similar rewriting algorithms have been devised for CQA [ABC, CM, FM, KG]

Results

- Tractable subclasses identified for ACS

query \ constraints	Ground	Finitely-closed A*	A*
E*	P	P	P
E*A*	P	P	Open
A*E*	P	NP-Complete	NP-Complete
CALC	P	NP-Complete	NP-Complete

† Finitely-closed means the set of constraints has a finite closure under resolution.

ACS: Ground conjunctive queries

- $Q = p(a,1) \land p(b,1)$
- $C = \{$
  $\forall\ x1\ x2\ y\ (\neg p(x1,y) \lor \neg p(x2,y) \lor x1=x2)$
  $\}$
- Q contradicts C.
- Answer: NO
- Rewrite:
  Q' = False

ACS: qf conjunctive queries

- $Q(x1,y1,x2,y2) = p(x1,y1) \wedge p(x2,y2)$
- $C = \{$
  $\forall\ x1\ x2\ y\ (\neg p(x1,y) \vee \neg p(x2,y) \vee x1{=}x2) \quad \}$
- $Q(x1,y1,x2,y2)$ is consistent w.r.t. C if and only if $(x1{=}x2 \vee y1{\neq}y2)$
- Rewrite:
  $Q' = Q(x1,x2,y1,y2) \wedge (x1{=}x2 \vee y1{\neq}y2)$

ACS: $\forall^*$ queries

- $Q = \forall x,y\ (\neg q(x,y) \lor \neg r(x,y))$
- $C = \{\ \forall x\ q(x,x)\ \}$
- $\neg q(x,y) \lor \neg r(x,y)$
  $q(x,x)$

  $\neg r(x,x)$

- Rewrite:
  $Q' = Q \land \forall x\ \neg r(x,x)$

Ongoing work

- Identify other tractable classes
- Recursive queries and aggregates
- Other answer semantics
  - preferentially-defeasible data?
  - coarser granularity?
  - Semantics that consider history?

Issues

- Constraint Language
  - Expressiveness (Skolems, aggregates)
  - Evaluation and Rewriting Techniques
- Managing Inconsistency
  - Inconsistencies and interdependencies
  - Automatic update in the presence of inconsistencies
  - Queries in the presence of inconsistencies
- Dynamic Constraints
  - Update Preferences
- Workflow Analysis, Use, Design
  - Privacy and Security
  - Promoting Convergence

References

[ABC] M. Arenas, L. Bertossi, and J. Chomicki. *Consistent query answers in inconsistent databases*. Symposium on principles of database systems, Pages 68–79, 1999.

[CM] J. Chomicki and J. Marcinkowski. *Minimal-change integrity maintenance using tuple deletions*. Inf. Comput.,197(1-2):90–121, 2005.

[FM] A. Fuxman and R. J. Miller. *First-order query rewriting for inconsistent databases*. J. Comput. Syst. Sci., 73(4):610–635, 2007.

[KG] E. Kao and M. Genesereth. *Answers with consistent support – complexity and rewriting.* Working paper, 2010.