Logic-based information integration

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Logic-based information integration: overview

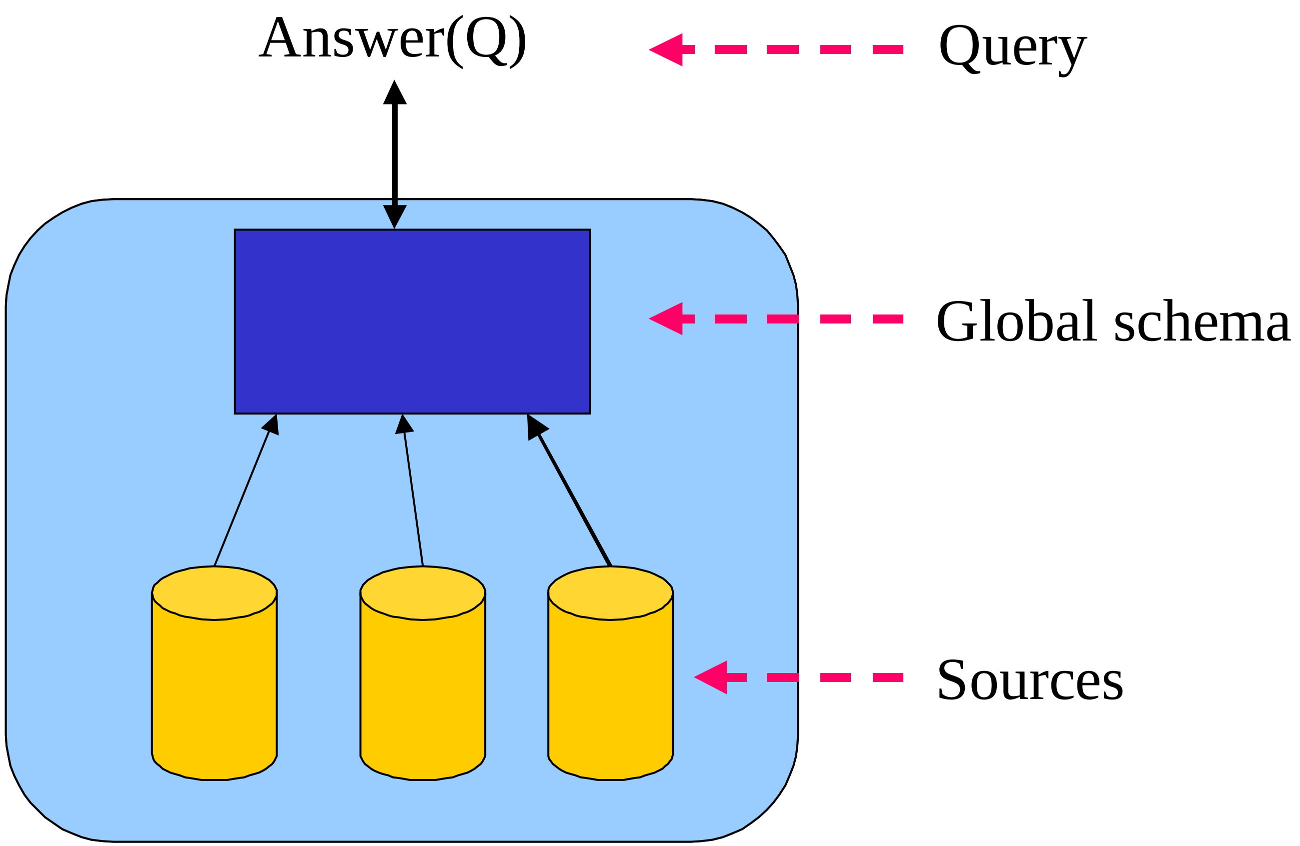
- Introduction to information (data) integration – *De Giacomo*
- Query answering in GAV and LAV information integration systems – *De Giacomo*
- Information integration under constraints: basic techniques – *Rosati*
- Information integration under constraints: results – *Rosati*
- Inconsistency tolerance in information integration – *Rosati*

  (see also Bertossi's ESSLLI'05 course)

Lecture 2: outline

- Query answering in information integration
- Query answering in GAV information integration systems
- Query answering in LAV information integration systems

Information integration



Query answering in different approaches

The problem of query answering comes in different forms, depending on several parameters:

- **Global schema**
  - without constraints (i.e., empty theory)
  - with constraints
- **Mapping**
  - GAV
  - LAV (or GLAV)
- **Queries**
  - user queries
  - queries in the mapping

Conjunctive queries

- Unless otherwise specified, we consider **conjunctive queries** (or, unions thereof) as both user queries and queries in the mapping.
- A conjunctive query has the form

$$\{\ (\vec{\mathbf{x}}) \mid \exists \vec{\mathbf{y}}\ \ p_1(\vec{\mathbf{x}}, \vec{\mathbf{y}}) \wedge \cdots \wedge p_m(\vec{\mathbf{x}}, \vec{\mathbf{y}})\ \}$$

- *Conjunctive query are also known as Select-Project-Join queries in Databases, and are the most common (and most optimizable) kind of queries.*

Incompleteness and inconsistency

Query answering heavily depends upon whether incompleteness/inconsistency shows up.

Constraints in $\mathcal{G}$	Type of mapping	Incompleteness	Inconsistency
no	GAV	**yes**/no	no
no	(G)LAV	**yes**	no
yes	GAV	**yes**	**yes**
yes	(G)LAV	**yes**	**yes**

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- Query answering in LAV information integration systems

Incompleteness and inconsistency

Constraints in $\mathcal{G}$	Type of mapping	Incompleteness	Inconsistency
no	*GAV*	**yes**/no	no
no	(G)LAV	**yes**	no
yes	GAV	**yes**	**yes**
yes	(G)LAV	**yes**	**yes**

Retrieved global database

Given a source database $\mathcal{C}$, we call **retrieved global database**, denoted $\mathcal{M}(\mathcal{C})$, the global database obtained by "applying" the queries in the mapping, and "transferring" to the elements of $\mathcal{G}$ the corresponding retrieved tuples.

GAV: example

Consider $\mathcal{I} = \langle \mathcal{G}, \mathcal{S}, \mathcal{M} \rangle$, with

Global schema $\mathcal{G}$:

$$\mathsf{student}(code, name, city)$$

$$\mathsf{university}(code, name)$$

$$\mathsf{enrolled}(Scode, Ucode)$$

Source schema $\mathcal{S}$: relations $\mathsf{s}_1(X, Y, W, Z)$, $\mathsf{s}_2(X, Y)$, $\mathsf{s}_3(X, Y)$

Mapping $\mathcal{M}$:

$$\mathsf{student}(X, Y, Z) \rightsquigarrow \{ (X, Y, Z) \mid \mathsf{s}_1(X, Y, Z, W) \}$$

$$\mathsf{university}(X, Y) \rightsquigarrow \{ (X, Y) \mid \mathsf{s}_2(X, Y) \}$$

$$\mathsf{enrolled}(X, W) \rightsquigarrow \{ (X, W) \mid \mathsf{s}_3(X, W) \}$$

GAV: example

university

code	name
AF	*bocconi*
BN	*ucla*

student

code	name	city
15	*bill*	*oslo*
12	*anne*	*florence*

enrolled

Scode	Ucode
12	*AF*
16	*BN*

$s_1^{\mathcal{C}}$

12	anne	florence	21
15	bill	oslo	24

$s_2^{\mathcal{C}}$

AF	bocconi
BN	ucla

$s_3^{\mathcal{C}}$

12	AF
16	BN

Example of source database $\mathcal{C}$ and corresponding retrieved global database $\mathcal{M}(\mathcal{C})$

GAV: minimal model

GAV mapping assertions $g \leadsto \phi_{\mathcal{S}}$ have the logical form:

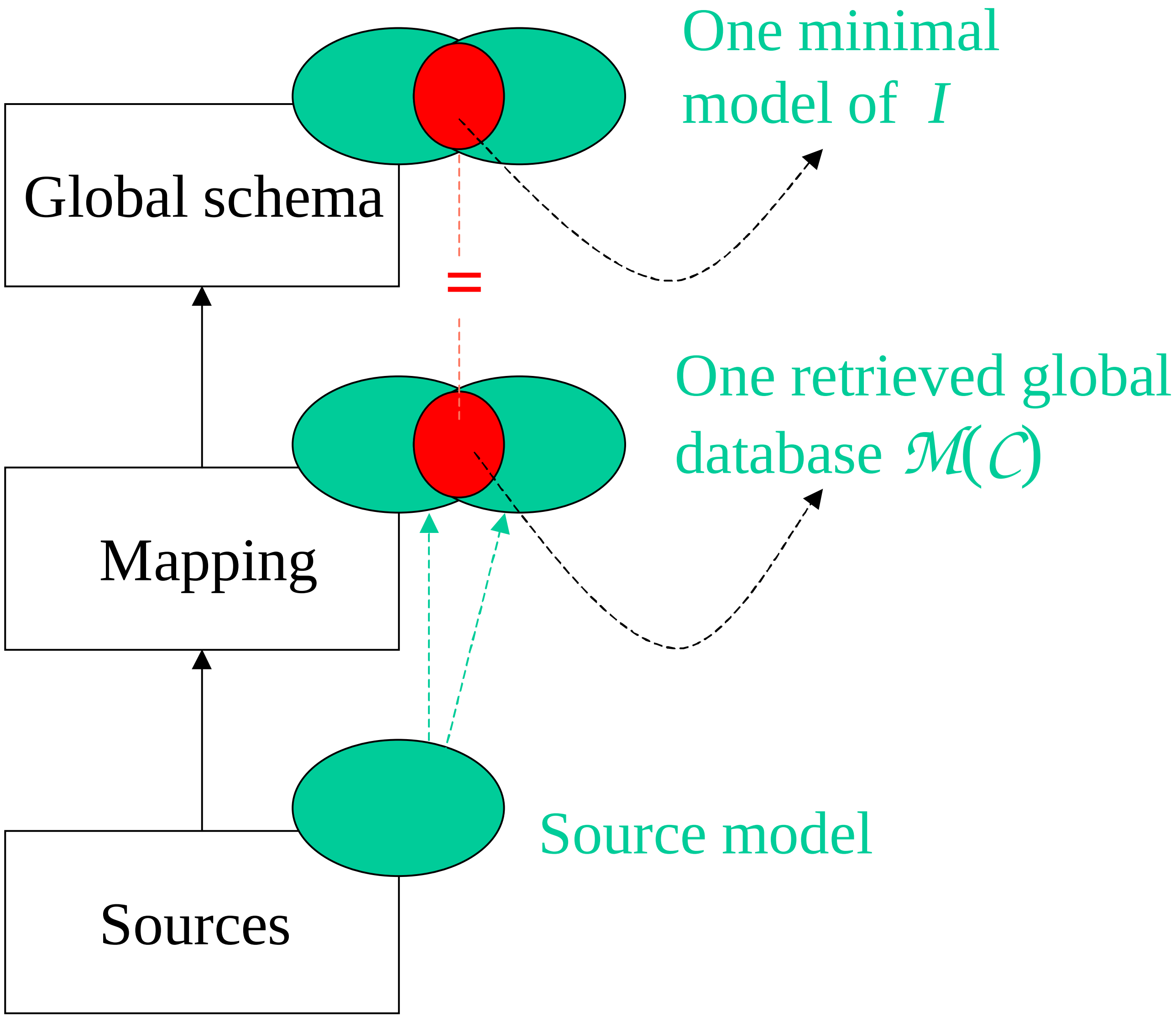
$$\forall \vec{\mathbf{x}} \;\; \phi_{\mathcal{S}}(\vec{\mathbf{x}}) \rightarrow g(\vec{\mathbf{x}})$$

where $\phi_{\mathcal{S}}$ is a conjunctive query, and g is an element of $\mathcal{G}$.

In general, given a source database $\mathcal{C}$ there are several databases that are legal wrt $\mathcal{G}$ that satisfies $\mathcal{M}$ wrt $\mathcal{C}$.

However, it is easy to see that $\mathcal{M}(\mathcal{C})$ is the intersection of all such databases, and therefore, is the **only** "minimal" model of $\mathcal{I}$.

GAV


Global schema
Mapping
Sources
One minimal
model of I
=
One retrieved global
database $\mathcal{M}(\mathcal{C})$
Source model

GAV: query answering

- If q is a conjunctive query, then $\vec{\mathbf{t}} \in cert(q, \mathcal{I}, \mathcal{C})$ if and only if $\vec{\mathbf{t}} \in q^{\mathcal{M}(\mathcal{C})}$
- If q is query over $\mathcal{G}$, then the unfolding of q wrt $\mathcal{M}$, *unf*$_{\mathcal{M}}(q)$, is the query over $\mathcal{S}$ obtained from q by substituting every symbol g in q with the query $\phi_{\mathcal{S}}$ that $\mathcal{M}$ associates to g
- It is easy to see that evaluating a query q over $\mathcal{M}(\mathcal{C})$ is equivalent to evaluating *unf*$_{\mathcal{M}}(q)$ over $\mathcal{C}$. It follows that, if q is a conjunctive query, then
  $\vec{\mathbf{t}} \in cert(q, \mathcal{I}, \mathcal{C})$ if and only if $\vec{\mathbf{t}} \in$*unf*$_{\mathcal{M}}(q)^{\mathcal{C}}$

  Unfolding is therefore sufficient
- **Data complexity** of query answering is **polynomial** (actually **LOGSPACE**): the query *unf*$_{\mathcal{M}}(q)$ is first-order (in fact conjunctive)
- Also, combined complexity is polynomial ($|\mathcal{M}(\mathcal{C})|$ is polynomial wrt $|\mathcal{C}|$)

GAV: example

university

code	name
AF	*bocconi*
BN	*ucla*

student

code	name	city
15	*bill*	*oslo*
12	*anne*	*florence*

{ x | student(15,x,y) }

unfolding

$s_1^{\mathcal{C}}$

12	*anne*	*florence*	21
15	*bill*	*oslo*	24

$s_2^{\mathcal{C}}$

AF	*bocconi*
BN	*ucla*

$\{ \, x \mid s_1(15, x, y, z) \, \}$

GAV: more expressive queries?

- More expressive queries in the mapping?
  - Same results hold if we use any computable query in the mapping
- More expressive user queries?
  - Same results hold if we use Datalog queries as user queries
  - Same results hold if we use union of conjunctive queries with inequalities as user queries

GAV: another view

Let B_1 and B_2 be two global databases with values in $\Gamma \cup$ Var.

- A homomorphism $h : B_1 \longrightarrow B_2$ is a mapping from ($\Gamma \cup$ Var(B_1)) to ($\Gamma \cup$ Var(B_2)) such that
  1. $h(c) = c$, for every $c \in \Gamma$
  2. for every fact $R_i(t)$ of B_1, we have that $R_i(h(t))$ is a fact in B_2 (where, if $t = (a_1, \ldots, a_n)$, then $h(t) = (h(a_1), \ldots, h(a_n))$)
- B_1 is homomorphically equivalent to B_2 if there is a homomorphism $h : B_1 \longrightarrow B_2$ and a homomorphism $h' : B_2 \longrightarrow B_1$

Let $\mathcal{I} = \langle \mathcal{G}, \mathcal{S}, \mathcal{M} \rangle$ be a data integration system. If $\mathcal{C}$ is a source database, then a universal solution for $\mathcal{I}$ relative to $\mathcal{C}$ is a model J of $\mathcal{I}$ relative to $\mathcal{C}$ such that for every model J' of $\mathcal{I}$ relative to $\mathcal{C}$, there exists a homomorphism $h : J \longrightarrow J'$ (see [Fagin&al. ICDT'03]).

GAV: another view

- Homomorphism preserves satisfaction of conjunctive queries: if there exists a homomorphism $h : J \rightarrow J'$, and q is a conjunctive query, then $\vec{\mathbf{t}} \in q^J$ implies $\vec{\mathbf{t}} \in q^{J'}$
- Let $\mathcal{I} = \langle \mathcal{G}, \mathcal{S}, \mathcal{M} \rangle$ be a GAV data integration system without constraints in the global schema. If $\mathcal{C}$ is a source database, then $\mathcal{M}(\mathcal{C})$ is the minimal universal solution for $\mathcal{I}$ relative to $\mathcal{C}$
- We derive again the following results
  - if q is a conjunctive query, then $\vec{\mathbf{t}} \in cert(q, \mathcal{I}, \mathcal{C})$ if and only if $\vec{\mathbf{t}} \in q^{\mathcal{M}(\mathcal{C})}$
  - complexity of query answering is polynomial

Lecture 2: outline

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Incompleteness and inconsistency

Constraints in $\mathcal{G}$	Type of mapping	Incompleteness	Inconsistency
no	GAV	**yes**/no	no
no	*(G)LAV*	**yes**	no
yes	GAV	**yes**	**yes**
yes	(G)LAV	**yes**	**yes**

(G)LAV: example

Consider $\mathcal{I} = \langle \mathcal{G}, \mathcal{S}, \mathcal{M} \rangle$, with

Global schema $\mathcal{G}$:

$$\text{student}(code, name, city)$$

$$\text{enrolled}(Scode, Ucode)$$

Source schema $\mathcal{S}$: relation $\text{s}_1(X, Y, W, Z)$

Mapping $\mathcal{M}$:

$$\{ (X, Y, Z) \mid \text{s}_1(X, Y, Z, W) \} \leadsto \{ (X, Y, Z) \mid \text{student}(X, Y, Z) \wedge \text{enrolled}(X, W) \}$$

(G)LAV: example

$$\{ (X,Y,Z) \mid \mathsf{s}_1(X,Y,Z,W) \} \rightsquigarrow \{ (X,Y,Z) \mid \mathsf{student}(X,Y,Z) \wedge \mathsf{enrolled}(X,W) \}$$

student

code	name	city
15	*bill*	*oslo*
12	*anne*	*florence*

enrolled

Scode	Ucode
15	***x***
12	***y***

$s_1^{\mathcal{C}}$

15	*bill*	*oslo*	24
12	*anne*	*florence*	21

A source database $\mathcal{C}$ and a corresponding possible retrieved global database $\mathcal{M}(\mathcal{C})$

(G)LAV: example

$$\{ (X, Y, Z) \mid \mathsf{s}_1(X, Y, Z, W) \} \leadsto \{ (X, Y, Z) \mid \mathsf{student}(X, Y, Z) \wedge \mathsf{enrolled}(X, W) \}$$

student

code	name	city
15	*bill*	*oslo*
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enrolled

Scode	Ucode
15	***x***
12	***x***

$s_1^{\mathcal{C}}$

15	*bill*	*oslo*	24
12	*anne*	*florence*	21

A source database $\mathcal{C}$ and another possible retrieved global database $\mathcal{M}(\mathcal{C})$

(G)LAV: incompleteness

(G)LAV mapping assertions $\phi_{\mathcal{S}} \leadsto \phi_{\mathcal{G}}$ have the logical form:

$$\forall \vec{\mathbf{x}} \;\; \phi_{\mathcal{S}}(\vec{\mathbf{x}}) \longrightarrow \exists \vec{\mathbf{y}} \phi_{\mathcal{G}}(\vec{\mathbf{x}}, \vec{\mathbf{y}})$$

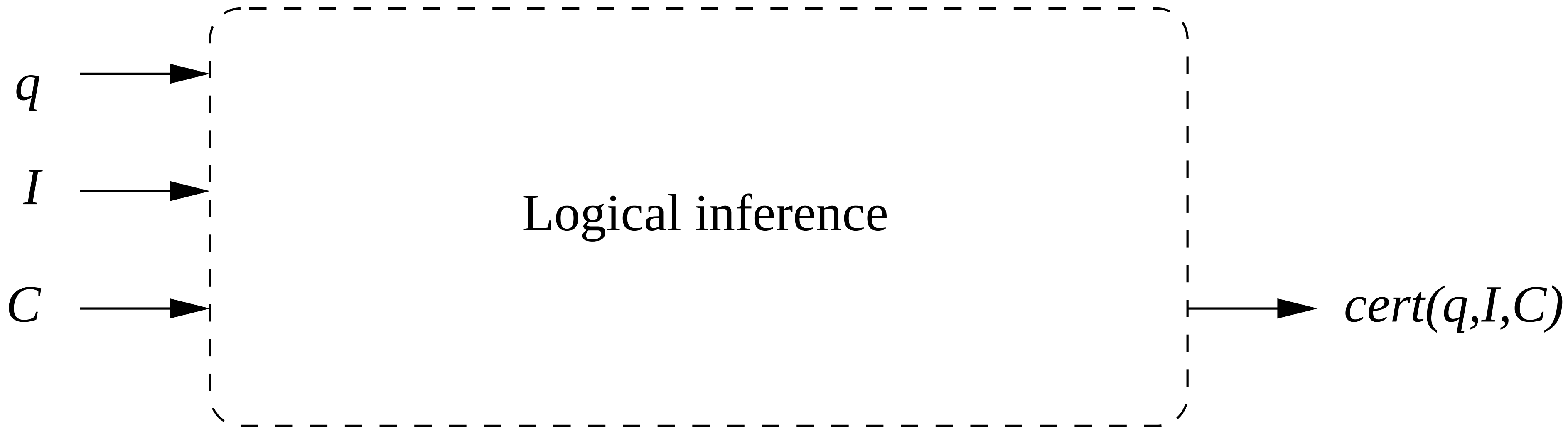
where $\phi_{\mathcal{S}}$ and $\phi_{\mathcal{G}}$ are conjunctions of atoms.

In general, given a source database $\mathcal{C}$ there are several solutions for a set of assertions of the above form (i.e., different databases that are legal wrt $\mathcal{G}$ that satisfies $\mathcal{M}$ wrt $\mathcal{C}$): **incompleteness comes from the mapping**.

This holds even for the case of very simple queries $\phi_{\mathcal{G}}$:

$$s_1(x) \;\; \leadsto \;\; \{\ (x) \mid \exists y\, g(x, y)\ \}$$

Query answering is based on logical inference



Approaches to query answering in (G)LAV systems

- Exploit connection with query containment
- Direct methods (aka view-based query answering)
- By (view-based) query rewriting

In (G)LAV data integration the views are the sources

Connection to query containment

Query containment (under constraints $\mathcal{T}$) *is the problem of checking whether $q_1^{\mathcal{B}}$ is contained in $q_2^{\mathcal{B}}$ for every database $\mathcal{B}$ (satisfying $\mathcal{T}$), where q_1, q_2 are queries with the same arity*.

- A source database $\mathcal{C}$ can be represented as a conjunction $q_{\mathcal{C}}$ of ground literals over $\mathcal{A}_{\mathcal{S}}$ (e.g., if $\vec{\mathbf{x}}$ is in $s^{\mathcal{C}}$, then the corresponding literal is $s(\vec{\mathbf{x}})$)
- If q is a query, and $\vec{\mathbf{t}}$ is a tuple, then we denote by $q_{\vec{\mathbf{t}}}$ the query obtained by substituting the free variables of q with $\vec{\mathbf{t}}$
- The problem of checking whether $\vec{\mathbf{t}} \in cert(q, \mathcal{I}, \mathcal{C})$ under sound sources can be reduced to the problem of checking whether $q_{\mathcal{C}}$ **is contained in $q_{\vec{\mathbf{t}}}$ under the constraints $\mathcal{G} \cup \mathcal{M}$**

The **combined complexity** of checking certain answers under sound sources is identical to the complexity of query containment under constraints, and the **data complexity** is at most the complexity of query containment under constraints.

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(G)LAV: basic technique

From [Duschka&Genesereth PODS'97]:

$$\mathsf{r}_1(T) \leadsto \{ (T) \mid \mathsf{movie}(T, Y, D) \land \mathsf{european}(D) \}$$

$$\mathsf{r}_2(T, V) \leadsto \{ (T, V) \mid \mathsf{movie}(T, Y, D) \land \mathsf{review}(T, V) \}$$

$$\forall T\, \mathsf{r}_1(T) \rightarrow \exists Y \exists D\, \mathsf{movie}(T, Y, D) \land \mathsf{european}(D)$$

$$\forall T\, \forall V\, \mathsf{r}_2(T, V) \rightarrow \exists Y \exists D\, \mathsf{movie}(T, Y, D) \land \mathsf{review}(T, V)$$

$$\mathsf{movie}(T, f_1(T), f_2(T)) \leftarrow \mathsf{r}_1(T)$$

$$\mathsf{european}(f_2(T)) \leftarrow \mathsf{r}_1(T)$$

$$\mathsf{movie}(T, f_4(T, V), f_5(T, V)) \leftarrow \mathsf{r}_2(T, V)$$

$$\mathsf{review}(T, V) \leftarrow \mathsf{r}_2(T, V)$$

- Answering a query means evaluating a goal wrt to this nonrecursive logic program (that can be transformed into a union of conjunctive query)
- PTIME (actually LOGSPACE) data complexity

(G)LAV: canonical retrieved global database

What is a retrieved global database in this case?

We build what we call the **canonical retrieved global database** for $\mathcal{I}$ relative to $\mathcal{C}$, denoted $\mathcal{M}(\mathcal{C})\!\downarrow$, as follows:

- let all predicates be empty in $\mathcal{M}(\mathcal{C})\!\downarrow$
- for each mapping assertion $\phi_{\mathcal{S}} \leadsto \phi_{\mathcal{G}}$ in $\mathcal{M}$
  - for each tuple $\vec{\mathbf{t}} \in \phi_{\mathcal{S}}^{\mathcal{C}}$ such that $\vec{\mathbf{t}} \notin \phi_{\mathcal{G}}^{\mathcal{M}(\mathcal{C})\downarrow}$, add $\vec{\mathbf{t}}$ to $\phi_{\mathcal{G}}^{\mathcal{M}(\mathcal{C})\downarrow}$ by inventing fresh variables (Skolem terms) in order to satisfy the existentially quantified variables in $\phi_{\mathcal{G}}$

There is a unique (up to variable renaming) canonical retrieved global database for $\mathcal{I}$ relative to $\mathcal{C}$, that can be computed in polynomial time wrt the size of $\mathcal{C}$. $\mathcal{M}(\mathcal{C})\!\downarrow$ obviously satisfies $\mathcal{G}$, and is also called the **canonical model of $\mathcal{I}$ relative to $\mathcal{C}$**.

(G)LAV: example of canonical model

$$\{ (X,Y,Z) \mid \mathsf{s}_1(X,Y,Z,W)\} \leadsto \{ (X,Y,Z) \mid \mathsf{student}(X,Y,Z) \wedge \mathsf{enrolled}(X,W) \}$$

student

code	**name**	**city**
15	*bill*	*oslo*
12	*anne*	*florence*

enrolled

Scode	**Ucode**
15	***x***
12	***y***

$s_1^{\mathcal{C}}$

15	*bill*	*oslo*	24
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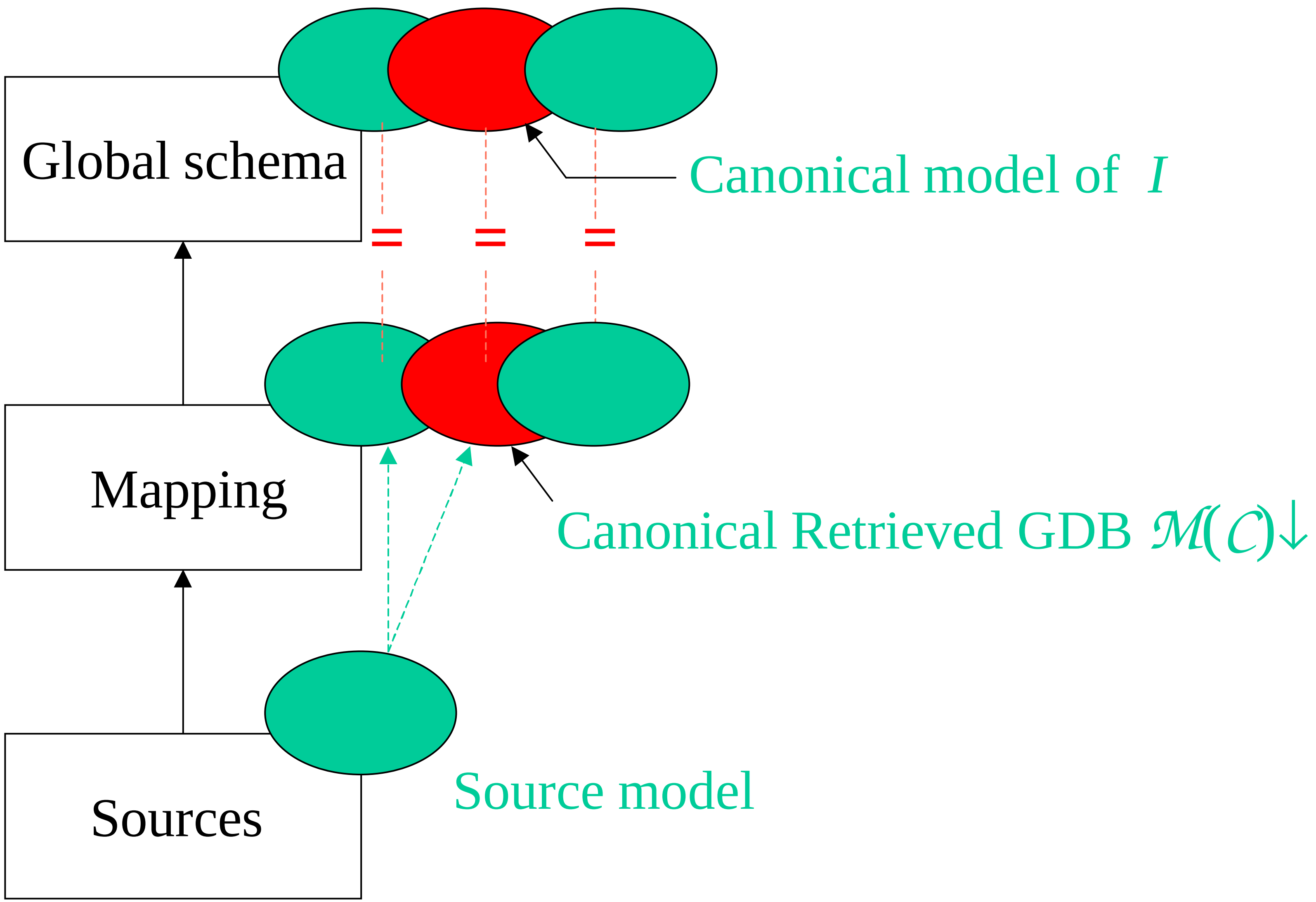
Example of source database $\mathcal{C}$ and corresponding canonical model $\mathcal{M}(\mathcal{C})\downarrow$

(G)LAV: canonical model



(G)LAV: universal solution

Let $\mathcal{I} = \langle \mathcal{G}, \mathcal{S}, \mathcal{M} \rangle$ be a (G)LAV data integration system without constraints in the global schema. If $\mathcal{C}$ is a source database, then $\mathcal{M}(\mathcal{C})\!\downarrow$ is a **universal solution** for $\mathcal{I}$ relative to $\mathcal{C}$ (follows from [Fagin&al. ICDT'03]).

It follows that:

- if q is a conjunctive query, then $\vec{\mathbf{t}} \in cert(q, \mathcal{I}, \mathcal{C})$ if and only if $\vec{\mathbf{t}} \in q^{\mathcal{M}(\mathcal{C})\downarrow}$
- complexity of query answering is **polynomial**

(G)LAV: more expressive queries?

- More expressive source queries in the mapping?
  - Same results hold if we use any computable query as source query in the mapping assertions
- More expressive queries over the global schema in the mapping?
  - Already positive queries lead to intractability
- More expressive user queries?
  - Same results hold if we use Datalog queries as user queries
  - Even the simplest form of negation (inequalities) leads to intractability

(G)LAV: data complexity

From [Abiteboul&Duschka PODS'98]:

Sound sources	CQ	$CQ^{\neq}$	PQ	Datalog	FOL
CQ	**PTIME**	**coNP**	**PTIME**	**PTIME**	**undec.**
$CQ^{\neq}$	**PTIME**	**coNP**	**PTIME**	**PTIME**	**undec.**
PQ	**coNP**	**coNP**	**coNP**	**coNP**	**undec.**
Datalog	**coNP**	**undec.**	**coNP**	**undec.**	**undec.**
FOL	**undec.**	**undec.**	**undec.**	**undec.**	**undec.**

(G)LAV: intractability for positive queries and views

From [Calvanese&al. ICDE'00], given a graph $G = (N, E)$, we define $\mathcal{I} = \langle \mathcal{G}, \mathcal{S}, \mathcal{M} \rangle$ and source database $\mathcal{C}$, with $\mathcal{S} = \{V_b, V_f, V_e\}$, and $\mathcal{G} = \{R_b, R_f, R_{rg}, R_{gr}, R_{rb}, R_{br}, R_{gb}, R_{bg}\}$

$\mathcal{M}$:

$V_b \leadsto R_b$

$V_f \leadsto R_f$

$V_e \leadsto R_{rg} \vee R_{gr} \vee R_{rb} \vee R_{br} \vee R_{gb} \vee R_{bg}$

$\mathcal{C}$:

$$\begin{aligned} {V_b}^{\mathcal{C}} &= \{(c, a) \mid a \in N, c \notin N\} \\ {V_f}^{\mathcal{C}} &= \{(a, d) \mid a \in N, d \notin N\} \\ {V_e}^{\mathcal{C}} &= \{(a, b), (b, a) \mid (a, b) \in E\} \end{aligned}$$

Query q : $\{ (X, Z) \mid R_b(X, Y) \wedge M(Y, W) \wedge R_f(W, Z)\}$

where M describes all mismatched edge pairs (e.g., $\{(X, Z) \mid R_{rg}(X, Y) \wedge R_{rb}(Y, Z)\}$).

- If G is 3-colorable, then $\exists \mathcal{B}$ where M (and q) is empty, i.e. $(c, d) \notin cert(q, \mathcal{I}, \mathcal{C})$
- If G is not 3-colorable, then M is nonempty $\forall \mathcal{B}$, i.e. $(c, d) \in cert(q, \mathcal{I}, \mathcal{C})$

$\Longrightarrow$ **coNP-hard data complexity** for positive queries and positive views.

(G)LAV: in coNP for positive queries and views

In the case of positive queries and positive views:

- $\vec{\mathbf{t}} \notin cert(q, \mathcal{I}, \mathcal{C})$ if and only if there is a database $\mathcal{B}$ for $\mathcal{I}$ such that $\vec{\mathbf{t}} \notin q^{\mathcal{B}}$, and $\mathcal{B}$ satisfies $\mathcal{M}$ wrt $\mathcal{C}$
- Because of the form of $\mathcal{M}$

$$\forall \vec{\mathbf{x}} \, (\phi_{\mathcal{S}}(\vec{\mathbf{x}}) \;\rightarrow\; \exists \vec{\mathbf{y_1}} \alpha_1(\vec{\mathbf{x}}, \vec{\mathbf{y_1}}) \;\vee\; \ldots \;\vee\; \exists \vec{\mathbf{y_h}} \alpha_h(\vec{\mathbf{x}}, \vec{\mathbf{y_h}}))$$

  each tuple in $\mathcal{C}$ forces the existence of k tuples in any database that satisfies $\mathcal{M}$ wrt $\mathcal{C}$, where k is the maximal length of conjuncts in $\mathcal{M}$
- If $\mathcal{C}$ has n tuples, then there is a database $\mathcal{B}' \subseteq \mathcal{B}$ for $\mathcal{I}$ that satisfies $\mathcal{M}$ wrt $\mathcal{C}$ with at most $n \cdot k$ tuples. Since q is monotone, $\vec{\mathbf{t}} \notin q^{\mathcal{B}'}$
- Checking whether $\mathcal{B}'$ satisfies $\mathcal{M}$ wrt $\mathcal{C}$, and checking whether $\vec{\mathbf{t}} \notin q^{\mathcal{B}'}$ can be done in PTIME wrt the size of $\mathcal{B}'$

$\Longrightarrow$ **coNP data complexity** for positive queries and positive views.

(G)LAV: conjunctive user queries with inequalities

Consider the following $\mathcal{I} = \langle \mathcal{G}, \mathcal{S}, \mathcal{M} \rangle$ and the following query q (from [Fagin&al. ICDT'03]):

$$\mathcal{M} \quad : \quad s(X,Y) \rightsquigarrow \{\, (X,Y) \mid T(X,Z) \wedge T(Z,Y) \,\}$$

$$\mathcal{C} \quad : \quad \{\, s(a,a) \,\}$$

$$q \quad : \quad \{\, (\,) \mid T(X,Y) \ \wedge \ X \neq Y) \,\}$$

- $J_1 = \{T(a,a)\}$ is a solution, and $q^{J_1} = false$
- if J is a universal solution, then both $T(a,X)$ and $T(X,a)$ are in J, with $X \neq a$ (otherwise $T(a,a)$ would be true in every solution)

$\Longrightarrow$ $cert(q, \mathcal{I}, \mathcal{C}) = false$, but $q^J = true$ for every universal solution J for $\mathcal{I}$ relative to $\mathcal{C}$

$\Longrightarrow$ the notion of universal solution is not the right tool

(G)LAV: conjunctive user queries with inequalities

- still polynomial with one inequalities
- coNP algorithm: guess equalities on variables in the canonical retrieved global database
- coNP-hard with six inequalities (see [Abiteboul&Duschka PODS'98])
- open problem for a number of inequalities between two and five

$\Longrightarrow$ **coNP-complete** for conjunctive user queries with inequalities.

Approaches to query answering in (G)LAV systems

- Exploit connection with query containment
- Direct methods (aka view-based query answering)
- By (view-based) query rewriting

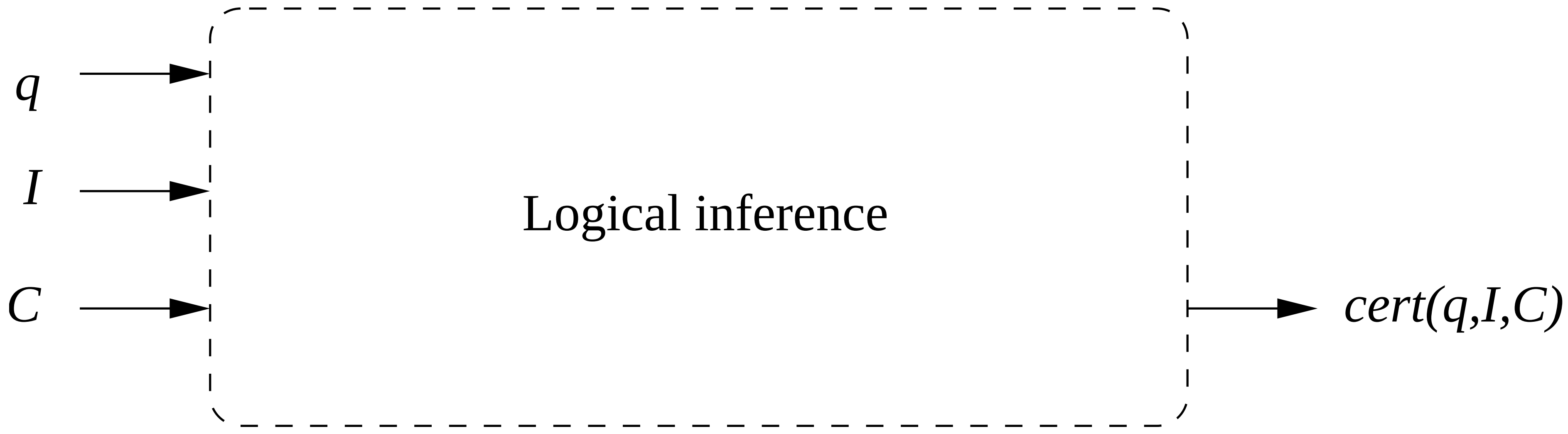
In (G)LAV data integration the views are the sources

(G)LAV: view-based query rewriting

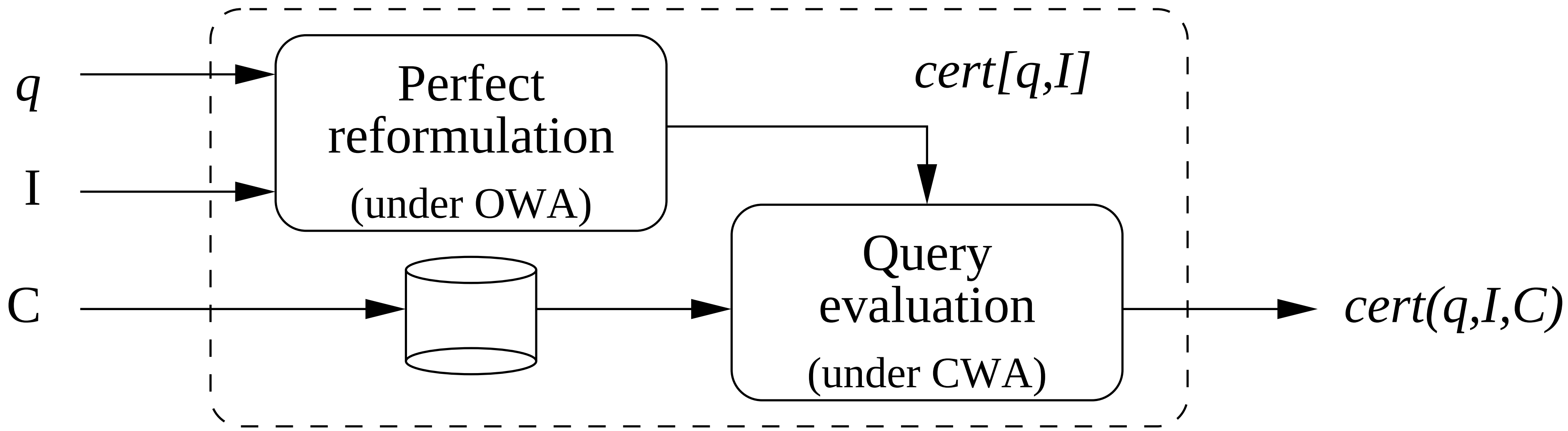
View-based query rewriting: query answering is divided in two steps

1. re-express the query in terms of a **given query language** over the alphabet of $\mathcal{A}_{\mathcal{S}}$
2. evaluate the rewriting over the source database $\mathcal{C}$

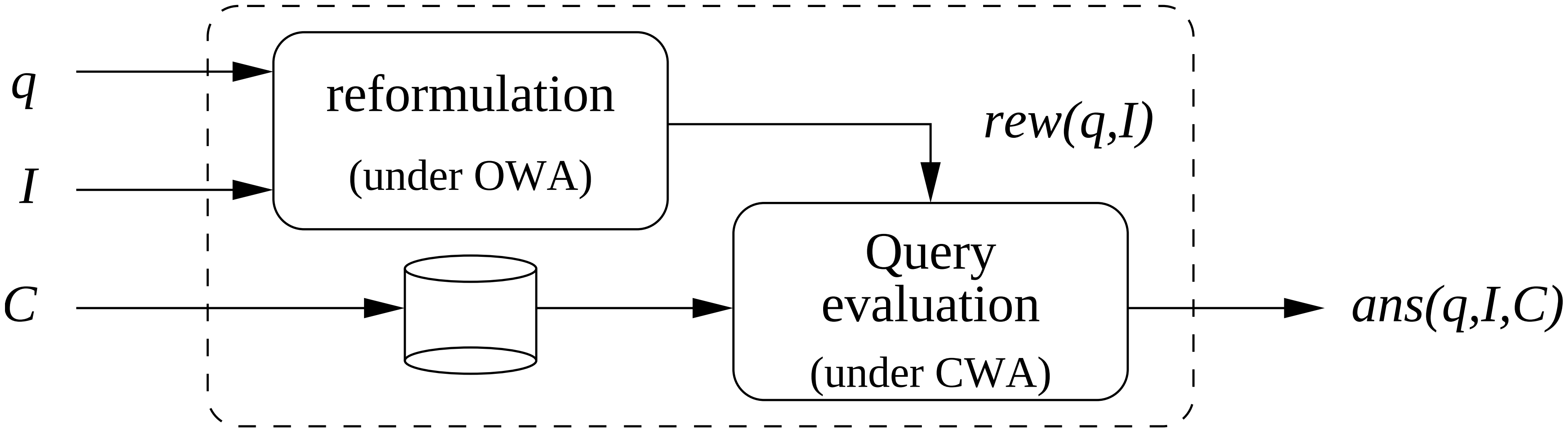
Query answering



Query answering: reformulation+evaluation



Query rewriting



The language of $rew(q, \mathcal{I})$ is chosen a priori!

(G)LAV: connection to rewriting

Query answering by rewriting:

- Given $\mathcal{I} = \langle \mathcal{G}, \mathcal{S}, \mathcal{M} \rangle$, and given a query q over $\mathcal{G}$, rewrite q into a query, called $rew(q, \mathcal{I})$, in the alphabet $\mathcal{A}_{\mathcal{S}}$ of the sources
- Evaluate the rewriting $rew(q, \mathcal{I})$ over the source database

We are interested in sound rewritings (i.e., computing only tuples in $cert(q, \mathcal{I}, \mathcal{C})$ for every source database $\mathcal{C}$) that are expressed in a given query language, and that are maximal for the class of queries expressible in such language.

Sometimes, we are interested in exact rewritings, i.e., rewritings that are logically equivalent to the query, modulo $\mathcal{M}$ (observe that such rewritings may not exists).

But (see [Calvanese &al. ICDT'05]):

- *When does the rewriting compute all certain answers?*
- *What do we gain or loose by focusing on a given class of queries?*

Perfect rewriting

Define $cert_{[q,\mathcal{I}]}(\cdot)$ to be the function that, with q and $\mathcal{I}$ fixed, given source database $\mathcal{C}$, computes the certain answers $cert(q, \mathcal{I}, \mathcal{C})$.

- $cert_{[q,\mathcal{I}]}$ can be seen as a query on the alphabet $\mathcal{A}_{\mathcal{S}}$
- $cert_{[q,\mathcal{I}]}$ is a (*sound*) rewriting of q wrt $\mathcal{I}$
- No sound rewriting exists that is better than $cert_{[q,\mathcal{I}]}$
- $cert_{[q,\mathcal{I}]}$ is called the **perfect rewriting** of q wrt $\mathcal{I}$

Properties of the perfect rewriting

- Can we express the perfect rewriting in a certain query language?
- How does a maximal rewriting for a given class of queries compare with the perfect rewriting?
  - From a semantical point of view
  - From a computational point of view
- Which is the computational complexity of (finding, evaluating) the perfect rewriting?

The case of conjunctive queries

Let $\mathcal{I} = \langle \mathcal{G}, \mathcal{S}, \mathcal{M} \rangle$ be a (G)LAV data integration system, let q and the queries in $\mathcal{M}$ be conjunctive queries (CQs), and let q' be the **union of all maximal rewritings of q for the class of CQs**. Then ([Levy&al. PODS'95], [Abiteboul&Duschka PODS'98]

- q' is the maximal rewriting for the class of unions of conjunctive queries (UCQs)
- **q' is the perfect rewriting of q wrt $\mathcal{I}$**
- q' is a PTIME query
- q' is an exact rewriting (equivalent to q for each database $\mathcal{B}$ of $\mathcal{I}$), if an exact rewriting exists

Does this "ideal situation" carry on to cases where q and $\mathcal{M}$ allow for union?

View-based query processing for UPQs

As we saw before, view-based query answering is coNP-complete in data complexity when we add (a very simple form of) union to the query language used to express queries over the global schema in the mapping [Calvanese&al. ICDE'00].

In other words, in this case $cert(q, \mathcal{I}, \mathcal{C})$, with q and $\mathcal{I}$ fixed, is a coNP-complete function, and therefore **the perfect rewriting $cert_{[q,\mathcal{I}]}$ is a coNP-complete query**.

If in the mapping we use a query language with union, then the perfect rewriting is coNP-hard — we do not have the ideal situation we had for conjunctive queries.

(G)LAV: Further references

- Inverse rules [Duschka&Genesereth PODS'97]
- Bucket algorithm for query rewriting [Levy&al. AAAI'96]
- MiniCon algorithm for query rewriting [Pottinger&Levy VLDB'00]
- Conjunctive queries using conjunctive views [Levy&al. PODS'95]
- Recursive queries (Datalog programs) using conjunctive views [Duschka&Genesereth PODS'97], [Afrati&al. ICDT'99]
- Conjunctive queries with arithmetic comparison [Afrati&al. PODS'01]
- Complexity analysis [Abiteboul&Duschka PODS'98] [Grahne&Mendelzon ICDT'99]
- Variants of Regular Path Queries [Calvanese&al. ICDE'00], [Calvanese&al. PODS'00], [Deutsch&Tannen DBPL'01], [Calvanese&al. DBPL'01],
- Relationship between view-based rewriting and answering [Calvanese&al. LICS'00], [Calvanese&al. PODS'03], [Calvanese&al. ICDT'05]