Reflections on Schema Mappings, Data Exchange, and Metadata Management

Phokion G. Kolaitis

UC Santa Cruz & IBM Research - Almaden

A Very Brief History

- Data exchange is the oldest database problem.
  Bernstein - 2003
- Yet, data exchange was not formalized until around 2000.
- Data exchange was formalized using schema mappings.
  - Schema Mappings as Query Discovery
    Miller, Haas, Hernández - VLDB 2000
  - Clio: A Semi-Automatic Tool for Schema Mapping
    Hernández, Miller, Haas - SIGMOD 2001
  - Data Exchange: Semantics and Query Answering
    Fagin, K . . ., Miller, Popa - ICDT 2003
- Extensive study of data exchange and schema mappings during the past 15 years.

Roadmap

Part I: Schema Mappings and Data Exchange

- Algorithmic and structural properties.

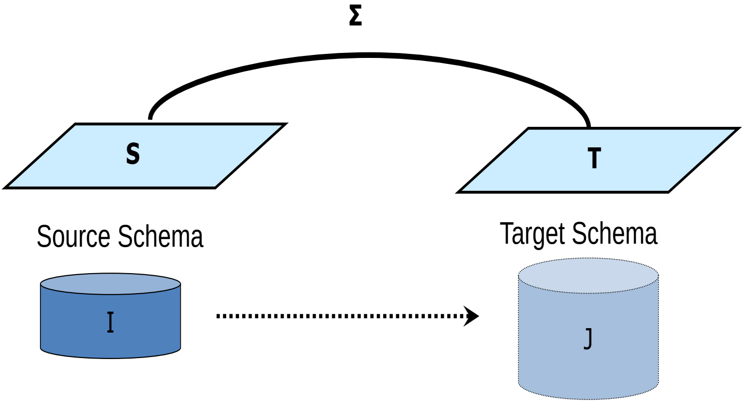
Part II: Operations on Schema Mappings

- Composing and inverting schema mappings.

Part III: Understanding and Deriving Schema Mappings

- Data examples to understand/derive schema mappings.

Data Exchange



Transform data structured under a source schema **S** into data structured a target schema **T**

Formalizing Data Exchange via Schema Mappings

Definition: A schema mapping is a triple $\mathcal{M} = (\mathbf{S}, \mathbf{T}, \mathcal{W})$ with

- $\mathbf{S}$ is a source schema, $\mathbf{T}$ is a target schema,
- $\mathcal{W}$ is a set of pairs (I, J) with I a source instance and J a target instance.

Syntactically, a schema mapping is a triple $\mathcal{M} = (\mathbf{S}, \mathbf{T}, \Sigma)$ with

- $\mathbf{S}$ is a source schema, $\mathbf{T}$ is a target schema,
- Σ is a set of constraints in some logical formalism expressing the relationship between $\mathbf{S}$ and $\mathbf{T}$.

$$(\mathrm{I}, \mathrm{J}) \models \Sigma \quad \text{if and only if} \quad (\mathrm{I}, \mathrm{J}) \in \mathcal{W}.$$

Definition: A solution for a source instance I with respect to $\mathcal{M}$ is a target instance J such that $(\mathrm{I}, \mathrm{J}) \in \mathcal{W}$ (or, $(\mathrm{I}, \mathrm{J}) \models \Sigma$).

Algorithmic Problems for Schema Mappings

Let $\mathcal{M} = (\mathbf{S}, \mathbf{T}, \mathcal{W})$ be a fixed schema mapping.

Existence of Solutions Problem:

Given a source instance I,

- determine whether or not a solution for I w.r.t. $\mathcal{M}$ exists;
- if so, compute a "good" solution for I w.r.t. $\mathcal{M}$.

Certain Answers Problem:

Let q be a fixed query over the target schema $\mathbf{T}$.

Given a source instance I,

- compute the certain answers of q on I w.r.t. $\mathcal{M}$

$$\text{cert}(q, \mathrm{I}, \mathcal{M}) = \bigcap \{q(\mathrm{J}) : \mathrm{J} \text{ is a solution for } \mathrm{I} \text{ w.r.t. } \mathcal{M}\}.$$

Schema-Mapping Languages

Question: What is a "good" schema-mapping language?

Ideally, a "good" schema-mapping language should have

- sufficient expressive power to express interesting data-transformation tasks;
- tractable algorithmic behavior.

Fact: The existence-of-solutions problem is undecidable for schema mappings specified by first-order sentences.

- Reduction from the finite validity problem for FO.

Basic Tasks for a Schema-Mapping Language

- Copy (Nicknaming):
  $\forall x_1, \ldots, x_n (P(x_1 \ldots, x_n) \rightarrow R(x_1, \ldots, x_n))$
- Projection:
  $\forall x, y, z (P(x, y, z) \rightarrow R(x, y))$
- Column Augmentation:
  $\forall x, y (P(x, y) \rightarrow \exists z R(x, y, z))$
- Decomposition:
  $\forall x, y, z (P(x, y, z) \rightarrow R(x, y) \land T(y, z))$
- Join:
  $\forall x, y, z (E(x, z) \land F(z, y) \rightarrow R(x, y, z))$
- Combinations of the above, e.g.,
  $\forall x, y, z (E(x, z) \land F(z, y) \rightarrow \exists w T(x, y, z, w)))$

Global-and-Local-As-View Constraints

Definition: A Global-and-Local-as-View (GLAV) constraint is a first-order sentence of the form

$$\forall \mathbf{x}(\varphi(\mathbf{x}) \to \exists \mathbf{y}\psi(\mathbf{x}, \mathbf{y})), \text{ where}$$

- $\varphi(\mathbf{x})$ is a conjunction of atoms over the source;
- $\psi(\mathbf{x}, \mathbf{y}))$ is a conjunction of atoms over the target.

Example:

$$\forall c, i, s(\text{ENROLLS}(s, c) \wedge \text{TEACHES}(i, c) \to \exists g\ \text{GRADES}(s, c, g))$$

Fact:
Each basic task (projection, decomposition, join, $\ldots$) can be expressed by a GLAV constraint.

GLAV, GAV, LAV Constraints and Mappings

- Global-and-Local-as-View (GLAV) constraint

$$\forall \mathbf{x}(\varphi(\mathbf{x}) \rightarrow \exists \mathbf{y}\psi(\mathbf{x}, \mathbf{y}))$$

- Global-As-View (GAV) constraint

  $\forall \mathbf{x}(\varphi(\mathbf{x}) \rightarrow R(\mathbf{x}))$, where R is a target relation.

  - Copy, Projection, Join

- Local-As-View (LAV) constraint

  $\forall \mathbf{x}(P(\mathbf{x}) \rightarrow \exists \mathbf{y}\psi(\mathbf{x}, \mathbf{y}))$, where P is a source relation.

  - Copy, Column Augmentation, Decomposition

- A GLAV mapping is a schema mapping $\mathcal{M} = (\mathbf{S}, \mathbf{T}, \Sigma)$, where Σ is a finite set of GLAV constraints.
- Similarly, for the notions of a GAV mapping and a LAV mapping.

Structural Properties of GLAV Mappings

Theorem (Fagin, K . . ., Miller, Popa - 2003)

Let $\mathcal{M} = (\mathbf{S}, \mathbf{T}, \Sigma)$ be a GLAV mapping.

- $\mathcal{M}$ admits universal solutions

For every source instance I, there is a solution J^* for I such that for every solution J for I, there is a homomorphism from J^* to J that is the identity on elements from I.

  - Moreover, such a J^* can be computed in polynomial time in the size of I via the chase procedure.

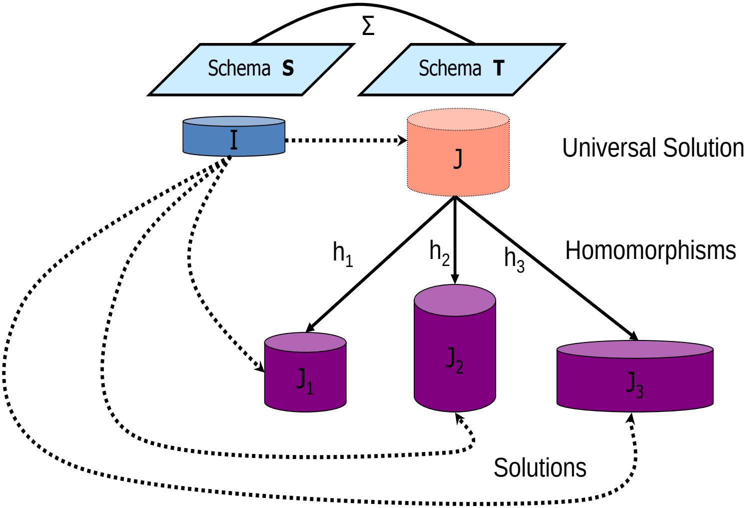
- $\mathcal{M}$ allows for CQ-rewriting

For every conjunctive query q over $\mathbf{T}$, there is a union q' of conjunctive queries over $\mathbf{S}$ such that

$$\mathrm{cert}(q, \mathrm{I}, \mathcal{M}) = q'(\mathrm{I}).$$

  - In particular, the certain answers of q can be computed in polynomial time in the size of I.

Universal Solutions in Data Exchange



Structural Properties of GLAV, GAV, & LAV Mappings

Proposition:

- Every GLAV mapping $\mathcal{M}$ is closed under target homomorphisms

If J is a solution for I and there is a homomorphism from J to J' that is the identity on elements of I, then J' is a solution for I.

- Every GAV mapping $\mathcal{M}$ is closed under target intersections

If J and J' are solutions for I, then $\mathrm{J} \cap \mathrm{J}'$ is a solution for I.

- Every LAV mapping $\mathcal{M}$ is closed under unions

If J is a solution for I and if J' is a solution for I', then $\mathrm{J} \cup \mathrm{J}'$ is a solution for $\mathrm{I} \cup \mathrm{I}'$.

Characterizing GAV and LAV Mappings

Theorem (ten Cate and K … - 2009)

Let $\mathcal{M} = (\mathbf{S}, \mathbf{T}, \mathcal{W})$ be a schema mapping. Then the following statements are equivalent:

1. $\mathcal{M}$ is logically equivalent to a GAV mapping (respectively, $\mathcal{M}$ is logically to a LAV mapping).
2. $\mathcal{M}$ has the following properties:
   - $\mathcal{M}$ admits universal solutions;
   - $\mathcal{M}$ allows for CQ-rewriting;
   - $\mathcal{M}$ is closed under target homomorphisms;
   - $\mathcal{M}$ is closed under target intersections (respectively, $\mathcal{M}$ is closed under unions).

Characterizing GLAV Mappings

Theorem (ten Cate and K ... - 2009)

Let $\mathcal{M} = (\mathbf{S}, \mathbf{T}, \mathcal{W})$ be a schema mapping. Then the following statements are equivalent:

1. $\mathcal{M}$ is logically equivalent to a GLAV mapping.
2. $\mathcal{M}$ has the following properties:
    - $\mathcal{M}$ admits universal solutions;
    - $\mathcal{M}$ allows for CQ-rewriting;
    - $\mathcal{M}$ is closed under target homomorphisms;
    - $\mathcal{M}$ is *n*-modular, for some $n \geq 1$.

Definition

A schema mapping $\mathcal{M} = (\mathbf{S}, \mathbf{T}, \mathcal{W})$ is *n-modular* if whenever $(\mathrm{I}, \mathrm{J}) \notin \mathcal{W}$, there is some $\mathrm{I}' \subseteq \mathrm{I}$ such that $|\mathrm{I}'| \leq n$ and $(\mathrm{I}', \mathrm{J}) \notin \mathcal{W}$.

Structural Characterizations: Summary

Type of Schema-Mapping	Characterizing Properties
GAV Mapping	admits universal solutions allows for $\mathcal{CQ}$-rewriting closed under target homomorphisms closed under target intersections
LAV Mapping	admits universal solutions allows for $\mathcal{CQ}$-rewriting closed under target homomorphisms closed under unions
GLAV Mapping	admits universal solutions allows for $\mathcal{CQ}$-rewriting closed under target homomorphisms n-modular, for some $n \geq 1$

Managing Schema Mappings via Operators

- Schema mappings can be quite complex.
- Methods and tools are needed to automate or semi-automate schema-mapping management.
- Metadata Management Framework - Bernstein 2003

  Based on generic schema-mapping operators:
  - Match operator
  - Merge operator
  - Composition operator
  - Inverse operator.
- Extensive study of the Composition operator and the Inverse operator.

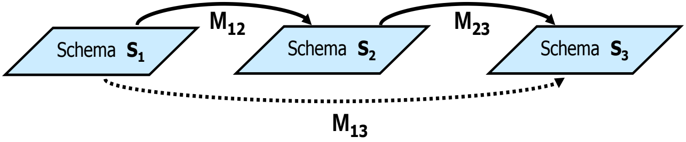
Composing Schema Mappings

Problem:

- Given $\mathcal{M}_{12} = (\mathbf{S_1}, \mathbf{S_2}, \Sigma_{12})$ and $\mathcal{M}_{23} = (\mathbf{S_2}, \mathbf{S_3}, \Sigma_{23})$, derive a schema mapping $\mathcal{M}_{13} = (\mathbf{S_1}, \mathbf{S_3}, \Sigma_{13})$ that is "equivalent" to the sequential application of $\mathcal{M}_{12}$ and $\mathcal{M}_{23}$.
- $\mathcal{M}_{13}$ is a composition of $\mathcal{M}_{12}$ and $\mathcal{M}_{23}$, denoted

$$\mathcal{M}_{13} = \mathcal{M}_{12} \circ \mathcal{M}_{23}.$$

- But, what does it mean to say that $\mathcal{M}_{13}$ is "equivalent" to the composition of $\mathcal{M}_{12}$ and $\mathcal{M}_{23}$?



Semantics of Composition

- Metadata Model Management Bernstein - 2003
  - Composition is one of the fundamental operators
  - However, no precise semantics is given.
- Composing Mappings among Data Sources
  Madhavan and Halevy - 2003
  - First to propose a semantics for composition
  - Notion of composition relative to a class of queries
  - CQ-composition: relative to the class of conjunctive queries
- Set-theoretic semantics of composition
  Fagin, K ..., Popa, Tan - 2004, Melnik - 2004

Set-theoretic Semantics of Composition

Recall that

- a syntactically specified $\mathcal{M} = (\mathbf{S}, \mathbf{T}, \Sigma)$

  is identified with

- the semantically specified $\mathcal{M} = (\mathbf{S}, \mathbf{T}, \mathcal{W}(\mathcal{M}))$, where

$$\mathcal{W}(\mathcal{M}) = \{(\mathrm{I}, \mathrm{J}) : (\mathrm{I}, \mathrm{J}) \models \Sigma\}.$$

Definition (FKPT - 2004, Melnik - 2004)
A schema mapping $\mathcal{M}_{13} = (\mathbf{S_1}, \mathbf{S_3}, \Sigma_{13})$ is the composition $\mathcal{M}_{12} \circ \mathcal{M}_{23}$ of $\mathcal{M}_{12} = (\mathbf{S_1}, \mathbf{S_2}, \Sigma_{12})$ and $\mathcal{M}_{23} = (\mathbf{S_2}, \mathbf{S_3}, \Sigma_{23})$ if

$$\mathcal{W}(\mathcal{M}_{13}) = \mathcal{W}(\mathcal{M}_{12}) \circ \mathcal{W}(\mathcal{M}_{23}),$$

i.e.,

- $(\mathrm{I}_1, \mathrm{I}_3) \in \mathcal{W}(\mathcal{M}_{13})$

  if and only if

- there is some I_2 such that $(\mathrm{I}_1, \mathrm{I}_2) \in \mathcal{W}(\mathcal{M}_{12})$ and $(\mathrm{I}_2, \mathrm{I}_3) \in \mathcal{W}(\mathcal{M}_{23})$.

The Language of Composition

Questions:

- Is the language of GLAV constraints closed under composition?

  In other words:

- If $\mathcal{M}_{12}$ and $\mathcal{M}_{23}$ are GLAV mappings, is $\mathcal{M}_{12} \circ \mathcal{M}_{23}$ a GLAV mapping as well?

- If not, what is the *right* language for composing schema mappings?

The Language of Composition

Theorem (Fagin, K ..., Popa, Tan - 2004)

- GAV mappings are closed under composition.
- GLAV mappings are not closed under composition.
- In fact, there are GLAV mappings $\mathcal{M}_{12}$ and $\mathcal{M}_{23}$ whose composition $\mathcal{M}_{12} \circ \mathcal{M}_{23}$ is not expressible even in least fixed-point logic LFP.

Question:
What is the *right* language for composing GLAV mappings?

Towards the “Right" Language for Composition

Motivating Example:

- $\mathcal{M}_{12}$:
  $\forall e(\mathrm{Emp}(e) \to \exists m \mathrm{Rep}(e, m))$
- $\mathcal{M}_{23}$:
  $\forall e \forall m(\mathrm{Rep}(e, m) \to \mathrm{Mgr}(e, m))$
  $\forall e(\mathrm{Rep}(e, e) \to \mathrm{SelfMgr}(e))$

Theorem:

- The composition $\mathcal{M}_{12} \circ \mathcal{M}_{23}$ is not definable by any set (finite or infinite) of GLAV constraints.
- The composition $\mathcal{M}_{12} \circ \mathcal{M}_{23}$ is definable by the following Second-Order GLAV constraint:

$$\exists f(\forall e(\mathrm{Emp}(e) \to \mathrm{Mgr}(e, f(e)) \wedge \forall e(\mathrm{Emp}(e) \wedge (e = f(e) \to \mathrm{SelfMgr}(e)))))$$

Second Order GLAV Constraints

Definition: Let **S** be a source schema and **T** a target schema. A Second-Order GLAV constraint (SO GLAV) is a formula of the form:

$$\exists f_1 \cdots \exists f_n ((\forall \mathbf{x}_1 (\varphi_1(\mathbf{x}_1) \rightarrow \psi_1(\mathbf{x}_1))) \wedge \cdots \wedge (\forall \mathbf{x}_n (\varphi_n(\mathbf{x}_1) \rightarrow \psi_n(\mathbf{x}_n)))),$$

where

- Each f_i is a function symbol.
- Each φ_i is a conjunction of atoms from **S** and equalities of terms.
- Each ψ_i is a conjunction of atoms from **T**.

Example: $\exists f (\forall e (\mathrm{Emp}(e) \rightarrow \mathrm{Mgr}(e, f(e)) \wedge$
$\forall e (\mathrm{Emp}(e) \wedge (e = f(e) \rightarrow \mathrm{SelfMgr}(e)))))$

Data Exchange via Second-Order GLAV Constraints

Theorem (Fagin, K ..., Popa, Tan - 2004)

- SO GLAV mappings are closed under composition.
- The chase procedure can be extended to SO GLAV mappings; in particular, it produces universal solutions in polynomial time.
- Every SO GLAV mapping is the composition of finitely many GLAV mappings (in fact, just two).

Conclusion: SO GLAV constraints are the right language for the composition of GLAV mappings.

Note: SO GLAV constraints and the composition algorithm are used in the IBM InfoSphere Information Server.

More on SO GLAV Mappings

Definition: A plain SO GLAV constraint is a SO GLAV constraint with no equalities $=$ and no nested function terms.

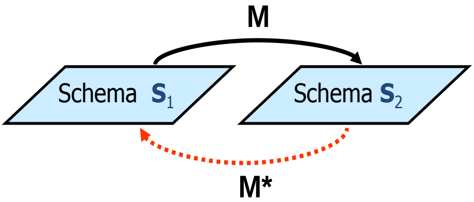
Theorem (Arenas, Pérez, Reutter, Riveros - 2013)

Plain SO GLAV constraints are the right language for the CQ-composition of GLAV mappings.

Open Problem 1:

- Is there a structural characterization of SO GLAV mappings?
- Is there a structural characterization of plain SO GLAV mappings?

Inverting Schema Mappings



Problem: Given a schema mapping **M**, find a schema mapping **M*** that "undoes" what **M** did.

Exact Inverses of Schema Mappings

Definition: Fagin - 2006
$\mathcal{M}^*$ is an inverse of $\mathcal{M}$ if $\mathcal{M} \circ \mathcal{M}^* = \mathrm{Id}$, where Id is the identity schema mapping specified by copy constraints.

Note: Schema mappings may entail inherent information loss.

- Union Schema Mapping

$$\forall \mathbf{x}(P(\mathbf{x}) \to Q(\mathbf{x}))$$
$$\forall \mathbf{x}(R(\mathbf{x}) \to Q(\mathbf{x}))$$

Fact: Inverses of GLAV mappings rarely exist.

Approximate Inverses of Schema Mappings

Several different approaches, including:

- Quasi-inverse
  Fagin, K . . ., Popa, Tan - 2007
- Maximum Recovery
  Arenas, Pérez, Riveros - 2008
- Chase Inverse
  Fagin, K . . ., Popa, Tan - 2011

Note:

- Maximum recoveries have better properties than other notions of approximate inverses do.
- In particular, every plain SO GLAV mapping has a maximum recovery (hence, so does every GLAV mapping).

Combining Composition and Inversion

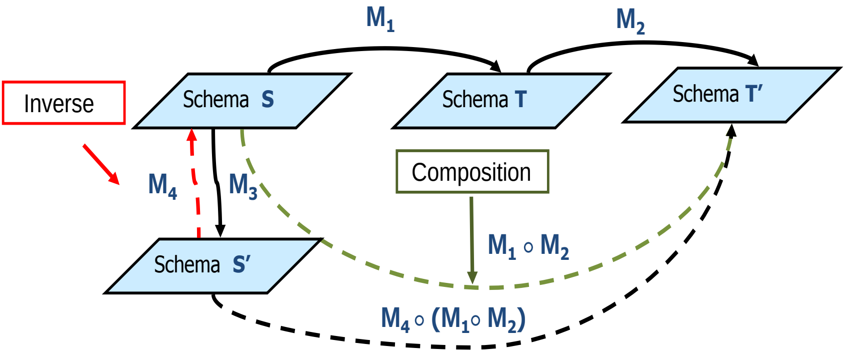
Fact:

- The language for expressing maximum recoveries involves disjunctive constraints.
- No definitive notion of an inverse has emerged.

Open Problem 2:

- Find a useful notion of inverse and a language for expressing it, so that the language is closed under compositions and inversions of GLAV mappings.

Evolution of Schema Mappings



Fact: Schema evolution can be analyzed using the composition operator and the inverse operator.

Schema Mappings Can Be Complex

```
Map 2:
        for  sm2x0 in S0.dummy_COUNTRY_4
        exists  tm2x0 in S27.dummy_country_10, tm2x1 in S27.dummy_organiza_13
           where  tm2x0.country.membership=tm2x1.organization.id,
        satisf  sm2x0.COUNTRY.AREA=tm2x0.country.area, sm2x0.COUNTRY.CAPITAL=tm2x0.country.capital,
                sm2x0.COUNTRY.CODE=tm2x0.country.id, sm2x0.COUNTRY.NAME=tm2x0.country.name,
                sm2x0.COUNTRY.POPULATION=tm2x0.country.population,(
        Map 3:
                for  sm3x0 in S0.dummy_GEO_RIVE_23, sm3x1 in S0.dummy_RIVER_24,
                        sm3x2 in S0.dummy_PROVINCE_5
                   where  sm3x0.GEO_RIVER.RIVER=sm3x1.RIVER.NAME, sm3x2.PROVINCE.NAME=sm3x0.GEO_RIVER.PROVINCE,
                        sm3x2.PROVINCE.COUNTRY=sm2x0.COUNTRY.CODE,
                exists  tm3x0 in S27.dummy_river_24, tm3x1 in tm3x0.river.dummy_located_23,
                        tm3x4 in S27.dummy_country_10, tm3x5 in tm3x4.country.dummy_province_9,
                        tm3x6 in S27.dummy_organiza_13
                where  tm3x4.country.membership=tm3x6.organization.id, tm3x5.province.id=tm3x1.located.province,
                        tm2x0.country.id=tm3x1.located.country,
                satisf  sm2x0.COUNTRY.AREA=tm3x4.country.area, sm2x0.COUNTRY.CAPITAL=tm3x4.country.capital,
                        sm2x0.COUNTRY.CODE=tm3x4.country.id, sm2x0.COUNTRY.NAME=tm3x4.country.name,
                        sm2x0.COUNTRY.POPULATION=tm3x4.country.population, sm3x1.RIVER.LENGTH=tm3x0.river.length,
                        sm3x0.GEO_RIVER.COUNTRY=tm3x1.located.country, sm3x0.GEO_RIVER.PROVINCE=tm3x1.located.province,
                        sm3x1.RIVER.NAME=tm3x0.river.name ),(
        Map 4:
                for  sm4x0 in S0.dummy_GEO_ISLA_25, sm4x1 in S0.dummy_ISLAND_26,
                        sm4x2 in S0.dummy_PROVINCE_5
                   where  sm4x0.GEO_ISLAND.ISLAND=sm4x1.ISLAND.NAME, sm4x2.PROVINCE.NAME=sm4x0.GEO_ISLAND.PROVINCE,
                        sm4x2.PROVINCE.COUNTRY=sm2x0.COUNTRY.CODE,
                exists  tm4x0 in S27.dummy_island_26, tm4x1 in tm4x0.island.dummy_located_25,
                        tm4x4 in S27.dummy_country_10, tm4x5 in tm4x4.country.dummy_province_9,
                        tm4x6 in S27.dummy_organiza_13
                   where  tm4x4.country.membership=tm4x6.organization.id, tm4x5.province.id=tm4x1.located.province,
                        tm2x0.country.id=tm4x1.located.country,
                satisf  sm2x0.COUNTRY.AREA=tm4x4.country.area, sm2x0.COUNTRY.CAPITAL=tm4x4.country.capital,
                        sm2x0.COUNTRY.CODE=tm4x4.country.id, sm2x0.COUNTRY.NAME=tm4x4.country.name,
                        sm2x0.COUNTRY.POPULATION=tm4x4.country.population, sm4x1.ISLAND.AREA=tm4x0.island.area,
                        sm4x1.ISLAND.COORDINATESLAT=tm4x0.island.latitude, sm4x0.GEO_ISLAND.COUNTRY=tm4x1.located.country,
                        sm4x0.GEO_ISLAND.PROVINCE=tm4x1.located.province, sm4x1.ISLAND.COORDINATESLONG=tm4x0.island.longitude,
                        sm4x1.ISLAND.NAME=tm4x0.island.name ),(
        Map 5:
                for  sm5x0 in S0.dummy_GEO_SEA_19, sm5x1 in S0.dummy_SEA_20,
                        sm5x2 in S0.dummy_PROVINCE_5
                   where  sm5x2.PROVINCE.NAME=sm5x0.GEO_SEA.PROVINCE, sm5x0.GEO_SEA.SEA=sm5x1.SEA.NAME,
                                sm5x2.PROVINCE.COUNTRY=sm2x0.COUNTRY.CODE,
                exists  tm5x0 in S27.dummy_sea_19, tm5x1 in tm5x0.sea.dummy_located_18,
                        tm5x4 in S27.dummy_country_10, tm5x5 in tm5x4.country.dummy_province_9,
                        tm5x6 in S27.dummy_organiza_13
                   where  tm5x4.country.membership=tm5x6.organization.id, tm5x5.province.id=tm5x1.located.province,
                        tm2x0.country.id=tm5x1.located.country,
                satisf  sm2x0.COUNTRY.AREA=tm5x4.country.area, sm2x0.COUNTRY.CAPITAL=tm5x4.country.capital,
```

Understanding and Deriving Schema Mappings

Idea:
Use data examples to understand/derive schema mappings

Theme I: From Syntax to Semantics
Understand schema mappings using data examples.

Theme II: From Semantics to Syntax:
Derive schema mappings using data examples.

Data Examples and Universal Examples

Definition: Let $\mathcal{M} = (\mathbf{S}, \mathbf{T}, \Sigma)$ be a schema mapping.

- A data example for $\mathcal{M}$ is a pair (I, J) such that J is a solution for I w.r.t. $\mathcal{M}$ (i.e., $(I, J) \models \Sigma$).
- A universal example for $\mathcal{M}$ is a pair (I, J) such that J is a universal solution for I w.r.t. $\mathcal{M}$.

Note: The space of data examples and the space of universal examples are typically infinite.

Question: Can a schema mapping $\mathcal{M} = (\mathbf{S}, \mathbf{T}, \Sigma)$ be captured by finitely many data examples or by finitely many universal examples?

From Syntax to Semantics: Unique Characterizations

Definition: Let $\mathcal{M} = (\mathbf{S}, \mathbf{T}, \Sigma)$ be a schema mapping, **U** set of universal examples for $\mathcal{M}$, and **C** a class of GLAV constraints.

- **U** uniquely characterizes $\mathcal{M}$ w.r.t. **C** if for every schema mapping $\mathcal{M}' = (\mathbf{S}, \mathbf{T}, \Sigma')$ such that $\Sigma' \subseteq \mathbf{C}$ and **U** is a set of universal examples for $\mathcal{M}'$, we have that $\Sigma \equiv \Sigma'$.

Note:

- Unique characterizability via finitely many positive/negative examples implies unique characterizability via finitely many universal examples, but not vice-versa.

From Syntax to Semantics: Unique Characterizations

Theorem (Alexe, ten Cate, K . . . , Tan - 2011)

- Every LAV mapping is uniquely characterizable by a finite set of universal examples w.r.t. to LAV constraints.
- Criterion for a GAV mapping to be uniquely characterizable by a finite set of universal examples w.r.t. GAV constraints.
- The associated decision problem for GAV mappings is NP-complete.

Open Problem 3:

- Find criteria for a GLAV mapping to by uniquely characterizable by a finite set of universal examples w.r.t. GLAV constraints.
- What is the exact complexity of the associated decision problem for GLAV mappings?

From Semantics to Syntax: Derivations

Interactive Derivation and Refinement of Schema Mappings

- Fitting Algorithm - EIRENE System
  Alexe, ten Cate, K . . ., Tan - 2011
- Interacting Mapping Specification with Exemplar Tuples - IMS System
  Bonifati, Comignani, Coquery, Thion - 2017

Deriving Optimal Schema Mappings from Data Examples

- Cost Model for Optimal Repairs of Schema Mappings
  Gottlob and Senellart - 2010
- Cost Model for Mapping Selection via Data Examples
  Kimmig, Memory, Miller, Getoor - 2017

From Semantics to Syntax: Learning

Theorem (ten Cate, Dalmau, K . . . - 2012)

GAV mappings are efficiently learnable in Angluin's model with membership and equivalence queries.

Active Learning of GAV Mappings

ten Cate, K . . ., Qian, Tan - PODS 2018

- Algorithm uses conformance testing as a substitute for the equivalence oracle.

Open Problem 4:

- Learnability of LAV mappings.
- Learnability of GLAV mappings.

Topics Not Covered - Partial List

- Richer schema mappings:
  - Schema mappings with target constraints
  - Schema mappings with arithmetic constraints
  - Schema mappings with bi-directional constraints.
- Alternative notions of solutions - Libkin 2006
- Alternative notions of certain answers
- Beyond conjunctive queries (non-monotonic, aggregate)
- XML Data Exchange - Arenas and Libkin 2005
- Benchmarks
  - STBenchmark - Alexe, Tan, Velegrakis 2008
  - iBench - Arocena, Glavic, Ciucanu, Miller 2015
  - Benchmarking the Chase - Benedikt et al. 2017.

Synopsis, Challenges, and Outlook

Synopsis

- Mature body of research during the past 15 years.
- A case study of logic *in* computer science, but also of logic *from* computer science.
- Theory and practice have informed each other.

Challenges and Outlook

- Several key technical problems remain open.
- Little penetration of advanced technical findings to practice.
- Benchmarks and open-source systems for data exchange need to be developed.