Schema Exchange: a Template-based Approach to Data and Metadata Translation

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Abstract. In this paper we study the problem of schema exchange, a natural extension of the data exchange problem to an intensional level. To this end, we first introduce the notion of schema template, a tool for the representation of a class of schemas sharing the same structure. We then define the schema exchange notion as the problem of (i) taking a schema that matches a source template, and (ii) generating a new schema for a target template, on the basis of a set of dependencies defined over the two templates. This framework allows the definition, once for all, of generic transformations that work for several schemas. A method for the generation of a "correct" solution of the schema exchange problem is proposed and a number of general results are given. We also show how it is possible to generate automatically a data exchange setting from a schema exchange solution. This allows the definition of queries to migrate data from a source database into the one obtained as a result of a schema exchange.

1 Introduction

In the last years, we have witnessed an increasing complexity of database applications, especially when several data sources need to be accessed, transformed and merged. There is a consequent growing need for advanced tools and flexible techniques supporting the management, the exchange, and the integration of different and heterogeneous sources of information.

In this trend, the data exchange problem has received recently great attention, both from a theoretical [12, 13] and a practical point of view [19]. In a data exchange scenario, given a set of correspondences between a source and a target schema, the goal is the automatic generation of queries able to transform data over the source into a format conforming to the target.

In this paper, we address the novel problem of *schema exchange*, which naturally extends the data exchange scenario to *sets* of similar schemas. To this aim, we first introduce the notion of *schema template*, which is used to represent a class of different database schemas sharing the same structure. Then, given a set of correspondences between the components of a source and a target template, the goal is the translation of any data source whose schema conforms to the source template into a format conforming to the target template. This framework allows the definition, once for all, of "generic" transformations that

works for different but similar schemas, such as the denormalization of a pair of relation tables based on a foreign key between them.

To tackle this problem, we introduce a formal notion of *solution* for a schema exchange setting and propose a technique for the automatic generation of solutions. This is done by representing constraints over templates and correspondences between them with a special class of first order formulas, and then using them to generate the solution by chasing [2] the source schema. Moreover, we show how it is possible to generate automatically a data exchange setting from a schema exchange solution. This allows the definition of a set of queries to migrate data from a source database into the database obtained as a result of the schema exchange.

From a practical point of view, in our scenario the user can: (i) describe a collection of databases presenting structural similarities, by means of a source template T_1, (ii) define the structure of a possible transformation of the source through a target template T_2, (iii) define how to exchange information from the source to the target by means of simple correspondences, graphically represented by lines between T_1 to T_2, and (iv) translate any data source over a schema matching with T_1 into a format described by a schema matching with T_2.

We advocate that the relational model is adequate for implementing such approach. In particular we show how existing repositories for relational database management systems can be profitably used for such purpose. In fact, templates can be stored in tables and can be then queried using a standard relational query language, independently of whether or not they are associated with some data.

To our knowledge, the notion of schema exchange studied in this paper is new. In general, we can say that our contribution can be set in the framework of *metadata management*. Metadata can generally be thought as information that describes, or supplements, actual data. Several studies have addressed metadata related problems, such as, interoperability [15, 20], annotations and comments on data [7, 10, 14], data provenance [9], and a large list of more specific problems, like data quality [17]. While the list is not exhaustive, it witnesses the large interest in this important area and the different facets of the problem.

Most of the proposed approach focus on a specific kind of metadata and are not directly applicable to other cases without major modifications. Bernstein set the various problems within a very general framework called *model management* [3–5]. In [6] the authors show the value of this framework to approach several metadata related problems, with a significant reduction of programming effort. Our contribution goes in this direction: as in model management, schemas and mappings are treated as first class citizens. In particular, the schema exchange problem has some points in common with the *ModelGen* operator. The ModelGen operator realizes a *schema translation* from a source data model M_s to a target data model M_t. For instance, the ModelGen operator could be used to translate an Entity-Relationship schema into a schema for an XML document (e.g., a DTD). Several approaches to this problem have been proposed in the last years [1, 8, 16, 18]. In this paper, we provide a novel contribution to this problem by studying a framework for schema translation with a clear and

precise semantics, that can be at the basis of an innovative tool supporting an important activity of model management.

The structure of the paper is as follows. In Section 2 we briefly set the basic definitions and recall some results of the data exchange problem. In Section 3, we introduce the notions of template and schema exchange and we show how they can be implemented with the relational database technology. In Section 4 we describes how templates and schemas are related and, in Section 5 we show how a data exchange problem can be obtained from a schema exchange setting. Finally, in Section 6, we draw some conclusions and sketch future directions of research.

2 Preliminaries

2.1 Basics

A *(relational) schema* $\mathbf{S}$ is composed by a set of *relations* $R(A_1, \ldots, A_n)$, where R is the *name* of the relation and $A_1, \ldots, A_k$ are its *attributes*. Each attribute is associated with a set of values called the *domain* of the attribute. An instance of a relation $R(A_1, \ldots, A_n)$ is a set of tuples, each of which associates with each A_i a value taken from its domain. An instance I of a schema $\mathbf{S}$ contains an instance of each relation in $\mathbf{S}$.

A *dependency* over a schema $\mathbf{S}$ is a first order formula of the form: $\forall \mathbf{x}(\phi(\mathbf{x}) \rightarrow \chi(\mathbf{x}))$ where $\phi(\mathbf{x})$ and $\chi(\mathbf{x})$ are formulas over $\mathbf{S}$, and $\mathbf{x}$ are the free variables of the formula, ranging over the domains of the attributes occurring in $\mathbf{S}$.

As usual, we will focus on two special kind of dependencies: the tuple generating dependencies (tgd) and the equality generating dependencies (egd), as it is widely accepted that they include all of the naturally-occurring constraints on relational databases. A tgd has the form: $\forall \mathbf{x}(\phi(\mathbf{x}) \rightarrow \exists \mathbf{y}(\psi(\mathbf{x}, \mathbf{y}))$ where $\phi(\mathbf{x})$ and $\psi(\mathbf{x}, \mathbf{y})$ are conjunction of atomic formulas, whereas an egd has the form: $\forall \mathbf{x}(\phi(\mathbf{x}) \rightarrow (x_1 = x_2))$ where $\phi(\mathbf{x})$ is a conjunction of atomic formulas and x_1, x_2 are variables in $\mathbf{x}$.

2.2 Data Exchange

In the relational-to-relational data exchange framework [12], a data exchange setting is described by $M = (\mathbf{S}, \mathbf{T}, \Sigma_{st}, \Sigma_t)$, where: (i) $\mathbf{S}$ is a source schema, (ii) $\mathbf{T}$ is a target schema, (iii) Σ_{st} is a finite set of *s-t* (source-to-target) tgds $\forall \mathbf{x}(\phi(\mathbf{x}) \rightarrow \exists \mathbf{y}(\chi(\mathbf{x}, \mathbf{y})))$ where $\phi(\mathbf{x})$ is a conjunction of atomic formulas over $\mathbf{S}$ and $\chi(\mathbf{x}, \mathbf{y})$ is a conjunction of atomic formulas over $\mathbf{T}$, and (iv) Σ_t is a finite set of tgs or egds over $\mathbf{T}$. Given an instance I of $\mathbf{S}$, a solution for I under M is an instance J of $\mathbf{T}$ such that (I, J) satisfies $\Sigma_{st} \cup \Sigma_t$. A solution may have distinct labeled nulls denoting unknown values.

In general, there are many possible solutions for I under M. A solution J is *universal* if there is a homomorphism from J to every other solution for I under M. A homomorphism from an instance I to an instance J is a function h from

constant values and nulls occurring in I to constant values and nulls occurring in J such that: (i) it is the identity on constants, and (ii) (with some abuse of notation) $h(I) \subseteq J$.

In [13] it was shown that a universal solution of I under M can be obtained by applying the chase procedure to I using $\Sigma_{st} \cup \Sigma_t$. This procedure takes as input an instance I and generates another instance by applying *chase steps* based on dependencies in $\Sigma_{st} \cup \Sigma_t$. There are two kinds of chase steps: (1) a tgd $\forall \mathbf{x}(\phi(\mathbf{x}) \rightarrow \exists \mathbf{y}(\psi(\mathbf{x}, \mathbf{y})))$ can be applied to I if there is a homomorphism h from $\phi(\mathbf{x})$ to I; in this case, the result of its application is $I \cup h'(\psi(\mathbf{x}, \mathbf{y}))$, where h' is the extension of h to $\mathbf{y}$ obtained by assigning fresh labeled nulls to the variables in $\mathbf{y}$; (2) an egd $\phi(x) \rightarrow (x_1 = x_2)$ can be applied to I if there is a homomorphism h from $\phi(\mathbf{x})$ to I such that $h(x_1) \neq h(x_2)$; in this case, the result of its application is the following: if one of $h(x_1)$ and $h(x_2)$ is a constant and the other is a variable then the variable is changed to the constant, otherwise the values are equated unless they are both constants, since in this case the process *fails*. The chase of I is obtained by applying all applicable chase steps exhaustively to I.

3 Schema Exchange Semantics

In this section we define the schema exchange problem as the application of the data exchange problem to *templates* of schemas.

3.1 Schema templates

We fix a finite set $\mathcal{C}$ of *construct names*. A *construct* $C(p_0, p_1, \ldots p_k)$ has a name C in $\mathcal{C}$ and a finite set $p_1, \ldots, p_k$ of distinct *properties*, each of which is associated with a set of values called the *domain* of the property. In principle, the set $\mathcal{C}$ can contain construct names from different data models so that we can define transformations between schemas of different models. In this paper however, for sake of simplicity, we focus on schema exchange between schema templates of relational schemas; the approach can be extended to other types of templates, but challenging issues already arise in the relational case.

Therefore, we fix the following relational construct names and properties:

Construct Names	Properties (domain)
Relation (or R)	name (strings)
Attribute (or A)	name (strings), nullable (booleans), in (strings)
AttributeKey (or AK)	name (strings), in (strings)
AttributeFKey (or AFK)	name (strings), in (strings), refer (strings)

Note that the Relation construct is associated only to the name property, whose domain is a set of strings. The same domain is also associated with the property in of the constructs Attribute, AttributeKey and AttributeFKey, and the property refer of the construct AttributeFKey: these properties are used to specify references between constructs. Clearly, other properties can be considered for every

construct. For instance, we could associate the properties type and has_default with the construct Attribute.

Basically, a template is a set of constructs with a set of dependencies associated with them, which are used to specify constraints over single constructs and semantic associations between different constructs.

Definition 1 (Template). *A* (schema) template *is a pair* $(\mathbf{C}, \Sigma_{\mathbf{C}})$*, where* $\mathbf{C}$ *is a finite collection of constructs and* $\Sigma_{\mathbf{C}}$ *is a set of dependencies over* $\mathbf{C}$*.*

Example 1. An example of a template $\mathcal{T} = (\mathbf{C}, \Sigma_{\mathbf{C}})$ contains the following set of constructs:

$$\mathbf{C} = \{\ \mathsf{Relation}(\mathsf{name}), \mathsf{AttributeKey}(\mathsf{name}, \mathsf{in}), \mathsf{Attribute}(\mathsf{name}, \mathsf{nullable}, \mathsf{in}), \\ \mathsf{AttributeFKey}(\mathsf{name}, \mathsf{in}, \mathsf{refer})\}$$

and the dependencies:

$$\begin{aligned}\Sigma_{\mathbf{C}} = \{\ & d_1 = \mathsf{AttributeKey}(n_K, n_R) \rightarrow \mathsf{Relation}(n_R), \\ & d_2 = \mathsf{Attribute}(n_A, u, n_R) \rightarrow \mathsf{Relation}(n_R), \\ & d_3 = \mathsf{AttributeFKey}(n_F, n_R, n'_R) \rightarrow \mathsf{Relation}(n_R), \mathsf{Relation}(n'_R), \\ & d_4 = \mathsf{Attribute}(n_A, u, n_R) \rightarrow (u = \mathtt{true})\}\end{aligned}$$

The tgds d_1 and d_2 state the membership of keys and attributes to relations, respectively. The dependency d_3 states the membership of a foreign key to a relation and its reference to another relation. Finally, the egd d_4 states that we are considering only relations with attributes that allow null values.

For simplicity, in the following we will omit the membership dependencies between constructs (like d_1, d_2 and d_3 in Example 1), assuming that they belong to $\Sigma_{\mathbf{C}}$.

Let us now introduce the notion of e-schemas. Basically, an e-schema corresponds to the *encoding* of a (relational) schema and is obtained by instantiating a template.

Definition 2 (E-schemas). *An* e-schema component S *over a construct* C *is a function that associates with each property* $p_1, \ldots, p_k$ *of* C *a value* a_i *taken from its domain. A* e-schema $\mathcal{S}$ *over a template* $(\mathbf{C}, \Sigma_{\mathbf{C}})$ *is a finite set of e-schema components over constructs in* $\mathbf{C}$ *that satisfy* $\Sigma_{\mathbf{C}}$*.*

Example 2. A valid e-schema for the template of Example 1 is the following:

Relation

name
EMP
DEPT

AttributeKey

name	in
EmpName	EMP
DeptNo	DEPT

Attribute

name	nullable	in
Salary	true	EMP
Building	true	DEPT

AttributeFKey

name	in	refer
Dept	EMP	DEPT

It is easy to see that this e-schema represents a relational table `EMP` with `EmpName` as key, `Salary` as attribute and `Dept` as foreign key, and a relational table `DEPT` with `DeptNo` as key and `Building` as attribute.

Note that e-schemas in Example 2 remind the common way commercial databases use to store metadata in catalogs. We can therefore easily verify whether a relational schema stored in a DBMS matches a given template definition: this can be done by querying the catalog of the system and checking the satisfaction of the dependencies.

In the following, an e-schema component over a construct $C(p_1, \ldots, p_k)$ will be called a *relation* component if $C = \mathsf{Relation}$, an *attribute* component if $C = \mathsf{Attribute}$, a *key* component if $C = \mathsf{AttributeKey}$, a *foreign key* component if $C = \mathsf{AttributeFKey}$. Moreover, we will denote an e-schema component over a construct $C(p_1, \ldots, p_k)$ by $C(p_1 : a_i, \ldots, p_k : a_k)$. Alternatively, we will use, for each construct, a tabular notation with a column for each property.

3.2 Schema exchange

Given a source template $\mathcal{T}_1 = (\mathbf{C}_1, \Sigma_{\mathbf{C}_1})$, a target template $\mathcal{T}_2 = (\mathbf{C}_2, \Sigma_{\mathbf{C}_2})$, and a set $\Sigma_{\mathbf{C}_1\mathbf{C}_2}$ of *source-to-target dependencies*, that is, a set of tgds on $\mathbf{C}_1 \cup \mathbf{C}_2$, we denote a *schema exchange setting* by the triple $(\mathcal{T}_1, \mathcal{T}_2, \Sigma_{\mathbf{C}_1\mathbf{C}_2})$.

Definition 3 (Schema exchange). *Let $(\mathcal{T}_1, \mathcal{T}_2, \Sigma_{\mathbf{C}_1\mathbf{C}_2})$ be a schema exchange setting and $\mathcal{S}_1$ a source e-schema over $(\mathbf{C}_1, \Sigma_{\mathbf{C}_1})$. The* schema exchange problem *consists in finding a finite target e-schema $\mathcal{S}_2$ over $(\mathbf{C}_2, \Sigma_{\mathbf{C}_2})$ such that $\mathcal{S}_1 \cup \mathcal{S}_2$ satisfies $\Sigma_{\mathbf{C}_1\mathbf{C}_2}$. In this case $\mathcal{S}_2$ is called* a solution for $\mathcal{S}_1$ *or, simply a* solution.

Example 3. Consider a schema exchange problem in which the source template $\mathcal{T}_1 = (\mathbf{C}_1, \Sigma_{\mathbf{C}_1})$ and the target template $\mathcal{T}_2 = (\mathbf{C}_2, \Sigma_{\mathbf{C}_2})$ are the following:

$$\mathbf{C}_1 = \{\, \mathsf{Relation}(\mathsf{name}), \mathsf{AttributeKey}(\mathsf{name}, \mathsf{in}), \mathsf{Attribute}(\mathsf{name}, \mathsf{in})\}$$

$$\mathbf{C}_2 = \{\, \mathsf{Relation}(\mathsf{name}), \mathsf{AttributeKey}(\mathsf{name}, \mathsf{in}), \mathsf{Attribute}(\mathsf{name}, \mathsf{in}), \mathsf{AttributeFKey}(\mathsf{name}, \mathsf{in}, \mathsf{refer})\}$$

with the corresponding membership constraints in $\Sigma_{\mathbf{C}_1}$ and in $\Sigma_{\mathbf{C}_2}$.

Assume now that we would like to split relations over $\mathcal{T}_1$ into a pair of relations over $\mathcal{T}_2$ related by a foreign key. This scenario is graphically shown (informally) in Figure 1 and is precisely captured by the following set of tgds $\Sigma_{\mathbf{C}_1,\mathbf{C}_2}$:

$$\begin{aligned}\Sigma_{\mathbf{C}_1,\mathbf{C}_2} = \{\, & \mathsf{Relation}(n_R), \mathsf{AttributeKey}(n_K, n_R), \mathsf{Attribute}(n_A, n_R) \rightarrow \\ & \mathsf{Relation}(n_R), \mathsf{AttributeKey}(n_K, n_R), \mathsf{AttributeFKey}(n_F, n_R, n'_R), \\ & \mathsf{Relation}(n'_R), \mathsf{AttributeKey}(n_F, n'_R), \mathsf{Attribute}(n_A, n'_R)\}\end{aligned}$$

Consider now the following e-schema valid for $\mathcal{T}_1$:

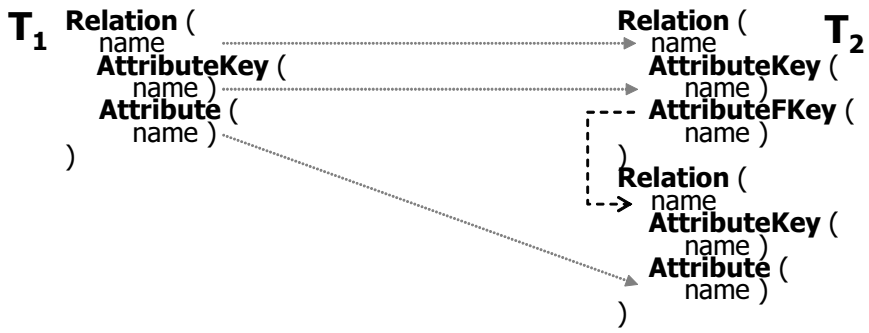


Fig. 1. Schema exchange scenario for Example 3

Relation
name
EMP

AttributeKey	
name	in
EmpName	EMP

Attribute	
name	in
DeptName	EMP
Floor	EMP

This e-schema has one relation called EMP with EmpName as key and two attributes: DeptName and Floor. A possible solution S_1' for this setting is:

Relation
name
EMP
N_0
N_2

AttributeKey	
name	in
EmpName	EMP
N_1	N_0
N_3	N_2

Attribute	
name	in
DeptName	N_0
Floor	N_2

AttributeFKey		
name	in	refer
N_1	EMP	N_0
N_3	EMP	N_2

where $N_0, \ldots, N_3$ are labelled nulls. This solution contains three relations: EMP, N_0 and N_2. Relation EMP has EmpName as key and N_1, N_3 as foreign keys for N_0 and N_2, respectively. Relation N_0 has N_1 as key and DeptName as attribute. Finally, relation N_2 has N_3 as key and Floor as attribute. There are several null values because the dependencies in $\Sigma_{\mathbf{C}_1,\mathbf{C}_2}$ do not allow the complete definition of the target e-schema.

Consider now another solution S_2':

Relation
name
EMP
N_0

AttributeKey	
name	in
EmpName	EMP
N_1	N_0

Attribute	
name	in
DeptName	N_0
Floor	N_0

AttributeFKey		
name	in	refer
N_1	EMP	N_0

with N_0 and N_1 as labelled nulls. This solution contains two relations named EMP and N_0. Relation EMP has EmpName as key and N_1 as foreign key, relation N_0 has N_1 as key and DeptName and Floor as attributes.

Two issues arise from Example 3: which solution to choose and how to generate it. Solution S_2' in the example seems to be less general than S_1'. This is captured

precisely by the notion of homomorphisms. In fact, it is easy to see that, while there is a homomorphisms from S_1' to S_2', there is no homomorphism from S_2' to S_1'. It follows that S_2' contains "extra" information whereas S_1' is a more general solution. As in data exchange [12, 13], we argue that the "correct" solution is the most general one, in the sense above. This solution is called universal.

Definition 4 (Universal solution). *A solution S of the schema exchange problem is* universal *if there exists a homomorphism from S to all other solutions.*

The following result follows from analogous results of the data exchange problem.

Theorem 1. *Let $(\mathcal{T}_1, \mathcal{T}_2, \Sigma_{\mathbf{C}_1\mathbf{C}_2})$ be a data exchange setting and S_1 be an e-schema over $\mathcal{T}_1$. The chase procedure over S_1 using $\Sigma_{\mathbf{C}_1\mathbf{C}_2} \cup \Sigma_{\mathbf{C}_2}$ terminates and generates a universal solution.*

4 Decoding and encoding of relational schemas

In this section we describe how the notion of e-schema introduced in Section 3 can be converted into a "standard" relational schema, and vice versa.

4.1 Relational decoding

Basically, the transformation of an e-schema in a relational schema requires the definition of formulas that describe the semantics of the various components of an e-schema, according to the intended meaning of corresponding constructs.

Let S be an e-schema over a template $\mathcal{T} = (\mathbf{C}, \Sigma_{\mathbf{C}})$. The *relational decoding* of S, denoted by R-DEC(S), is a pair $(\mathbf{S}, \Sigma_{\mathbf{S}})$ where:

- $\mathbf{S}$ contains a set of objects $R(A_1, \ldots, A_n)$ for each relation component $S \in \mathsf{S}$ such that:
  - $S(\mathsf{name}) = R$ and
  - $R = S_i(\mathsf{in})$ for the attribute components $S_1, \ldots, S_k$ in S such that $S_i(\mathsf{name}) = A_i$.
- $\Sigma_{\mathbf{S}}$ contains an egd over $R(A_1, \ldots, A_n) \in \mathbf{S}$ of the form:

$$R(x_1, x_2, \ldots, x_n), R(x_1, x_2', \ldots, x_n') \rightarrow (x_2 = x_2', \ldots, x_n = x_n')$$

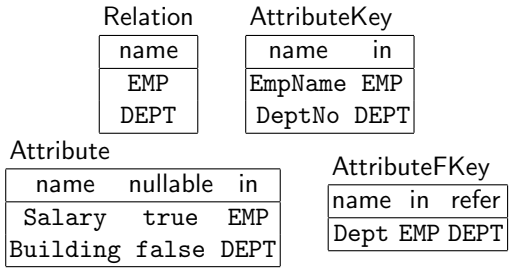
  for each key component $S \in \mathsf{S}$ such that:
  - $S(\mathsf{name}) = A_1$ and
  - $S(\mathsf{refer}) = R$.
- $\Sigma_{\mathbf{R}}$ contains a tgd over a pair of relation schemas $R(A_1, \ldots, A_k, \ldots, A_n)$ and $R'(A_k', A_1', \ldots, A_n')$ in $\mathbf{S}$ of the form:

$$R(x_1, \ldots, x_k, \ldots, x_m) \rightarrow R'(x_k, x_1', \ldots, x_n')$$

  for each foreign key component $S \in \mathsf{S}$ such that:

- $S(\mathsf{name}) = A_k$,
- $S(\mathsf{in}) = R$,
- $S(\mathsf{refer}) = R'$, and
- $R' = S'(\mathsf{in})$ for the key component S' in S such that $S'(\mathsf{name}) = A'_k$.

Example 4. Let us consider the e-schema S of Example 2 reported below:



The relational representation of S is: R-DEC(S) = $(\mathbf{S}, \Sigma_{\mathbf{S}})$ where:

$$\mathbf{S} = \{\mathtt{EMP}(\mathtt{EmpName}, \mathtt{Salary}, \mathtt{Dept}), \mathtt{DEPT}(\mathtt{DeptNo}, \mathtt{Building})\}$$

$$\begin{aligned}\Sigma_{\mathbf{S}} = \{\ & \mathtt{EMP}(x_1, x_2, x_3), \mathtt{EMP}(x_1, x'_2, x'_3) \rightarrow (x_2 = x'_2, x_3 = x'_3),\\ & \mathtt{DEPT}(x_1, x_2), \mathtt{DEPT}(x_1, x'_2) \rightarrow (x_2 = x'_2),\\ & \mathtt{EMP}(x_1, x_2, x_3) \rightarrow \mathtt{DEPT}(x_3, x'_2)\}\end{aligned}$$

In the same line, a procedure for the *encoding* of a relational schema, that is for the transformation of a relational schema $(\mathbf{S}, \Sigma_{\mathbf{S}})$ into an e-schema S, can also be defined. This procedure will be illustrated in the following section.

4.2 Relational encoding

Let $\mathbf{S}$ be a relational schema with a set of dependencies $\Sigma_{\mathbf{S}}$. The *encoding* of $\mathbf{S}$, denoted by R-ENC($\mathbf{S}, \Sigma_{\mathbf{S}}$), is an e-schema S such that:

- for each relation $R(A_1, \ldots, A_n)$ in $\mathbf{S}$, S has a relation component m such that $m(\mathsf{name}) = R$ and, for each attribute $A_i \in R$, S has an attribute component m_i such that:
  - $m_i(\mathsf{name}) = A_i$,
  - $m_i(\mathsf{nullable})$ =true if A_i is nullable,
  - $m_i(\mathsf{in}) = R$;
- for each egd in $\Sigma_{\mathbf{S}}$ of the form:

  $$R(x_1, x_2, \ldots, x_n), R(x_1, x'_2, \ldots, x'_n) \rightarrow (x_2 = x'_2, \ldots, x_n = x'_n)$$

  over a relation schema $R(A_1, \ldots, A_n) \in \mathbf{S}$, S has a key component m such that:
  - $m(\mathsf{name}) = A_i$, and
  - $m(\mathsf{in}) = R$;

– for each tgd in $\Sigma_{\mathbf{S}}$ of the form:

$$R(x_1, \ldots, x_k, \ldots, x_m) \rightarrow R'(x_k, x'_1, \ldots, x'_n)$$

over a pair of relation schemas $R(A_1, \ldots, A_k, \ldots, A_m)$ and $R'(A'_1, \ldots, A'_n)$ in $\mathbf{S}$, S has a foreign key component m such that:

- $m(\mathsf{name}) = A_k$,
- $m(\mathsf{in}) = R$, and
- $m(\mathsf{refer}) = R'$.

5 From Schema to Data Exchange

In this section we propose a transformation process that generates a data exchange from a given schema exchange setting.

5.1 Metaroutes and Value Correspondences

Before discussing the transformation process, two preliminary notions are needed. First of all, in order to convert the schema exchange setting into a *data* exchange setting, we need to keep track of the correspondences between the source schema and the solution of the schema exchange problem. This can be seen as an application of the data provenance problem to schema exchange. To this end, by extending to our context a notion introduced in [11], we make use of *metaroutes* to describe the relationships between source and target metadata.

Definition 5. *Let S be an e-schema and Σ be a set of dependencies. A* metaroute *for S is an expression of the form:*

$$I_0 \rightarrow_{\sigma_1, h_1} I_1 \ldots I_{n-1} \rightarrow_{\sigma_n, h_n} I_n$$

where $I_0 \subseteq \mathsf{S}$ and, for each $I_{i-1} \rightarrow_{\sigma_i, h_i} I_i$ $(1 \leq i \leq n)$, it is the case that I_i is the result of the application of a chase step on I_{i-1} based on the dependency $\sigma_i \in \Sigma$ and the homomorphism h_i.

Note that, since a reduced number of elements are involved in schema exchange, we can store all the metaroutes and we do not need to compute them partially and incrementally as in [11].

Metaroutes and homomorphisms are then used to derive *value correspondences* between source and target schemas.

Definition 6. *A* value correspondence *over two schemas $\mathbf{S}$ and $\mathbf{S}'$ is a triple $v = (t \in R, t' \in R', t.A_i = t'.A_j)$ where $R \in \mathbf{S}$, $R' \in \mathbf{S}'$, and $A_i = A_j$ is a set of equalities over the attributes of R and R', respectively.*

5.2 The S-D transformation process

Given a relational database over a schema $\mathbf{S}_1$ and schema exchange setting $(\mathcal{T}_1, \mathcal{T}_2, \Sigma_{\mathbf{C}_1\mathbf{C}_2})$ such that the encoding S_1 of $\mathbf{S}_1$ is an instance of $\mathcal{T}_1$, we aim at generating a target database over a schema $\mathbf{S}_2$ such that the encoding S_2 of $\mathbf{S}_2$ is a universal solution for S_1. We call such generation process S-D *transformation* and it can be summarized as follows.

1. $\mathbf{S}_1$ is encoded into an e-schema S_1;
2. the chase procedure is applied to S_1 using $\Sigma_{\mathbf{C}_1\mathbf{C}_2}$ and metaroutes are generated during the execution of the procedure: each chase step based on the dependency $\sigma_i \in \Sigma$ and the homomorphism h_i adds an element $I_{i-1} \rightarrow_{\sigma_i,h_i} I_i$ to the metaroute;
3. the result S_2 of the chase procedure is decoded into a schema $\mathbf{S}_2$;
4. for each attribute A occurring in $\mathbf{S}_2$: (i) we select the metaroute $I_0 \rightarrow_{\sigma_1,h_1} I_1 \ldots I_{n-1} \rightarrow_{\sigma_n,h_n} I_n$ such that A occur in I_n, and (ii) A is annotated in $\mathbf{S}_1$ and $\mathbf{S}_2$ with $h^{-1}(A)$, where $h = h_1 \circ \ldots \circ h_n$;
5. the annotations of the attributes in $\mathbf{S}_1$ and $\mathbf{S}_2$ are used to derive value correspondences between them;
6. a data exchange setting is generated from $\mathbf{S}_1$ and $\mathbf{S}_2$ using the generated value correspondences, on the basis of the method presented in [19].

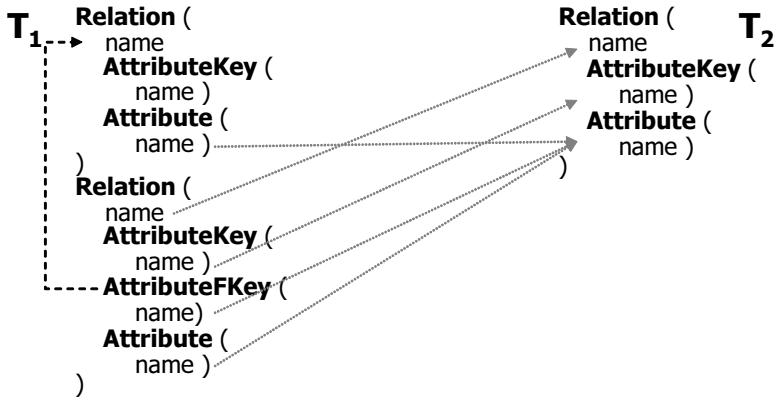


Fig. 2. Schema exchange scenario for Example 5.

Example 5. Let us consider the schema exchange setting described graphically in Figure 2 and represented by the following set of tgds $\Sigma_{\mathbf{C}_1,\mathbf{C}_2}$:

$$\{\ v_1 = \mathsf{Relation}(n_r), \mathsf{AttributeKey}(n_k, n_r), \mathsf{Attribute}(n_a, n_r), \mathsf{Relation}(n'_r), \mathsf{AttributeKey}(n'_k, n'_r), \mathsf{Attribute}(n'_a, n'_r), \mathsf{AttributeFKey}(n_f, n'_r, n_r) \rightarrow \mathsf{Relation}(n'_r), \mathsf{AttributeKey}(n'_k, n'_r), \mathsf{Attribute}(n'_a, n'_r), \mathsf{Attribute}(n_f, n'_r), \mathsf{Attribute}(n_a, n'_r)\ \}$$

Intuitively, the only constraint occurring in $\Sigma_{\mathbf{C}_1,\mathbf{C}_2}$ specifies that the target is obtained by joining two source relations according to a foreign key defined between them. Now consider the following source schema:

$$\mathbf{S} = \{\texttt{DEPT}(\texttt{id}, \texttt{dname}), \texttt{EMP}(\texttt{id}, \texttt{ename}, \texttt{dep})\}$$

$$\begin{aligned}\Sigma_{\mathbf{S}} = \{\ & \texttt{DEPT}(x_1, x_2), \texttt{DEPT}(x_1, x_2') \rightarrow (x_2 = x_2'),\\ & \texttt{EMP}(x_1, x_2, x_3), \texttt{EMP}(x_1, x_2', x_3') \rightarrow (x_2 = x_2', x_3 = x_3'),\\ & \texttt{EMP}(x_1, x_2, x_3) \rightarrow \texttt{DEPT}(x_3, x_1')\}\end{aligned}$$

The encoding of $\mathbf{S}$ is the e-schema S that follows:

Relation

	name
s_1	DEPT
s_2	EMP

AttributeKey

	name	in
s_3	id	DEPT
s_4	id	EMP

Attribute

	name	in
s_5	dname	DEPT
s_6	ename	EMP

AttributeFKey

	name	in	refer
s_7	dep	EMP	DEPT

Let $\{s_1, \ldots, s_7\}$ be the e-components of S. The application of the chase based on the given tgd produces the set of e-schema components $\{t_1, \ldots, t_5\}$:

Relation

	name
t_1	EMP

AttributeKey

	name	in
t_2	id	EMP

Attribute

	name	in
t_3	ename	EMP
t_4	dep	EMP
t_5	dname	EMP

The metaroute generated by this chase step is: $\{s_1, \ldots, s_7\} \rightarrow_{v_1,h_1} \{t_1, \ldots, t_5\}$, where h_1 is the homomorphism:

$$\{\ n_r \mapsto \texttt{DEPT}, n_k \mapsto \texttt{id}, n_a \mapsto \texttt{dname}, n_r' \mapsto \texttt{EMP}, n_k' \mapsto \texttt{id}, n_a' \mapsto \texttt{ename}, n_f \mapsto \texttt{dep}\}$$

The chase ends successfully and produces an e-schema S' whose decoding is the schema $(\mathbf{S}', \Sigma_{\mathbf{S}'})$ where:

$$\mathbf{S}' = \{\texttt{EMP}(\texttt{id}, \texttt{ename}, \texttt{dep}, \texttt{dname})\}$$

$$\Sigma_{\mathbf{S}'} = \{\ \texttt{DEPT}(x_1, x_2, x_3, x_4), \texttt{DEPT}(x_1, x_2', x_3', x_4') \rightarrow (x_2 = x_2', x_3 = x_3', x_4 = x_4')\}$$

Now, on the basis of the above metaroute, source and target schema can be annotated as follows:

$$\begin{aligned}\mathbf{S} &= \{\texttt{DEPT}(\texttt{id}[n_k], \texttt{dname}[n_a]), \texttt{EMP}(\texttt{id}[n_k'], \texttt{ename}[n_a'], \texttt{dep}[n_f])\}\\ \mathbf{S}' &= \{\texttt{EMP}(\texttt{id}[n_k'], \texttt{ename}[n_a'], \texttt{dep}[n_f], \texttt{dname}[n_a])\}\end{aligned}$$

The value correspondences between $\mathbf{S}$ and $\mathbf{S}'$ easily follow:

$$\begin{aligned}vc_1 &= (d \in \mathbf{S}.\texttt{DEPT}, e \in \mathbf{S}'.\texttt{EMP}, d.\texttt{dname} = e.\texttt{dname})\\ vc_2 &= (e \in \mathbf{S}.\texttt{EMP}, e' \in \mathbf{S}'.\texttt{EMP}, e.\texttt{id} = e'.\texttt{id}, e.\texttt{ename} = e'.\texttt{ename}, e.\texttt{dep} = e'.\texttt{dep})\end{aligned}$$

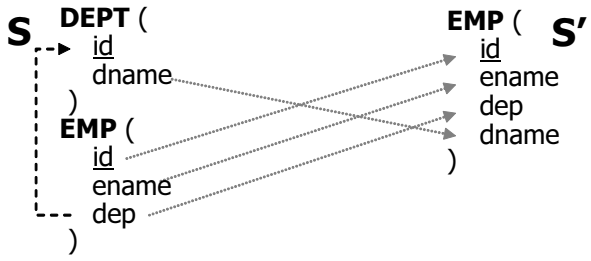


Fig. 3. Data exchange scenario for Example 5.

We then obtain the data mapping scenario reported graphically in Figure 3. In the spirit of [19] we are now able to automatically generate a data exchange setting. Given the source schema $\mathbf{S}$, the target schema $\mathbf{S}'$ with its constraints, and the value correspondences we obtain the following tgd:

$$t_1 = \mathtt{S.EMP}(ss, en, d), \mathtt{S.DEPT}(d, dn) \rightarrow \mathtt{S'.EMP}(ss, en, d, dn)$$

A number of general results can be shown. First, the fact that the output of the S-D process is a "correct" result, that is, the solution of the data exchange problem reflects the semantics of the schema exchange problem given as input. In order to introduce the concept of correctness in this context, a preliminary notion is needed.

Given a tgd t, an *encoding* of t is the tgd obtained by applying the encoding procedure defined in Section 4 considering the atoms of the formula as they were relational schemas and using the dependencies in $\Sigma_{\mathbf{S}}$ for the left side of t and the dependencies $\Sigma_{\mathbf{S}'}$ for the right side of t. Note that the tgd we obtain is defined on templates.

For instance, given the tgd t_1 of the example above, the encoding of t_1 is the following tgd on templates:

$$\begin{aligned} v_2 = {} & \mathsf{Relation}(\mathtt{EMP}), \mathsf{AttributeKey}(ss, \mathtt{EMP}), \mathsf{Attribute}(en, \mathtt{EMP}), \\ & \mathsf{AttributeFKey}(d, \mathtt{EMP}, \mathtt{DEPT}), \mathsf{Relation}(\mathtt{DEPT}), \mathsf{AttributeKey}(d, \mathtt{DEPT}), \\ & \mathsf{Attribute}(dn, \mathtt{DEPT}) \rightarrow \mathsf{Relation}(\mathtt{EMP}), \mathsf{AttributeKey}(ss, \mathtt{EMP}), \\ & \mathsf{Attribute}(en, \mathtt{EMP}), \mathsf{Attribute}(d, \mathtt{EMP}), \mathsf{Attribute}(dn, \mathtt{EMP}) \end{aligned}$$

This tgd v_2 is different from the original tgd v_1 for the schema exchange scenario described in Example 5. However, it can be verified that they generate the same output S′ on the given input S. This exactly captures the fact that the data exchange problem obtained as output fulfils the semantics of the schema exchange problem given as input.

This intuition is captured by the following correctness result.

Theorem 2. *Let* $(\mathbf{S}, \mathbf{S}', \Sigma_{\mathbf{SS}'})$ *be the output of the* S-D *transformation process when* $(\mathcal{T}_1, \mathcal{T}_2, \Sigma_{\mathbf{C}_1\mathbf{C}_2})$ *and* $\mathbf{S}$ *are given as input and let* $\overline{\Sigma}$ *be the set of s-t tgds*

obtained by encoding the s-t tgds in $\Sigma_{\mathbf{SS}'}$. *The e-schema* $\mathbf{S}'$ *is a universal solution of the schema exchange setting* $(\mathcal{T}_1, \mathcal{T}_2, \overline{\Sigma})$.

The following completeness result can also be shown. We say that a data exchange setting is *constant-free* if no constants are used in formulas.

Theorem 3. *Any constant-free data exchange setting can be obtained from the* S-D *transformation process over some schema exchange setting.*

6 Conclusion and Future work

We have introduced the schema exchange problem, a generalization of data exchange. This problem consists of taking a schema that matches a source template, and generating a new schema for a target template, on the basis of a set of dependencies defined over the two templates. To tackle this problem, we have presented a method for the generation of a "correct" solution of the problem and a process aimed at automatically generating a data exchange setting from a schema exchange solution.

We believe that several interesting directions of research can be pursued within this framework. We just sketch some of them.

- *Expressive power of the framework.* A challenging issue to be investigated is the precise identification of the class of schema and data transformations that can be defined with the framework we have defined. This is clearly related with the formulas used to express the mappings between templates. For instance, it is an open problem to identify the formalism needed to express a schema exchange that operates over a specific number of columns.
- *Metaquerying.* A template is actually a schema and it can therefore be queried. A query over a template is indeed a *meta* query since it operates over meta-data. There are a number of meta-queries that are meaningful. For instance, we can retrieve with a query over a template the pairs of relations that can be joined, being related by a foreign key. Also, we can verify whether there is a join path between two relations.
- *Special class of solutions.* Given a schema exchange problem, can we verify whether all the solutions of the problem satisfy some relevant property? For instance, we would like to obtain only relations that are acyclic or satisfy some normal form. We are also investigating under which conditions a schema exchange problem generates a data exchange setting with certain properties, e.g., the fact that the dependencies belong to some relevant class.
- *Combining data and metadata.* The framework we have presented can be extended to support mappings and constraints involving data and metadata at the same time. This scenario also allows the user to specify the transformation of metadata into data and vice versa. For instance, we could move the name of a relational attribute into a tuple of a relation.

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