Foundations of DATA EXCHANGE

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FOUNDATIONS OF DATA EXCHANGE

The problem of exchanging data between different databases with different schemas is an area of immense importance. Consequently data exchange has been one of the most active research topics in databases over the past decade. Foundational questions related to data exchange largely revolve around three key problems: how to build target solutions; how to answer queries over target solutions; and how to manipulate schema mappings themselves? The last question is also known under the name "metadata management", since mappings represent metadata, rather than data in the database.

In this book the authors summarize the key developments of a decade of research. Part I introduces the problem of data exchange via examples, both relational and XML; Part II deals with exchanging relational data; Part III focuses on exchanging XML data; and Part IV covers metadata management.

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To Magdalena, Marcelito and Vanny, for their love and support.
M. A.

To Salvador, Gabi and my parents.
P. B.

To my parents.
L. L.

To my grandparents, who chose to send their kids to university.
F. M.

Preface

Data exchange, as the name suggests, is the problem of exchanging data between different databases that have different schemas. One often needs to exchange data between existing legacy databases, whose schemas cannot be easily modified, and thus one needs to specify rules for translating data from one database to the other. These rules are known as schema mappings. Once a source database and a schema mapping are given, one needs to transfer data to the target, i.e., construct a target database. And once the target database is constructed, one needs to answer queries against it.

This problem is quite old; it has been studied, and systems have been built, but it was done in a rather ad hoc way. A systematic study of the problem of data exchange commenced with the 2003 paper "Data exchange: semantics and query answering" by Fagin, Kolaitis, Miller, and Popa, published in the proceedings of the International Conference on Database Theory. A large number of followup papers appeared, and for a while data exchange was one of the most active research topics in databases. Foundational questions related to data exchange largely revolved around three key problems:

1. how to build a target solution;
2. how to answer queries over target solutions; and
3. how to manipulate schema mappings themselves.

The last question is also known under the name of metadata management, since mappings represent metadata, rather than data in the database.

This book summarizes the key developments of the decade of research in the area of data exchange. It is organized into four parts.

In Part One, the problem of data exchange is introduced via examples, both relational and XML. We present key definitions: of schema mappings, of solutions (possible target instances), and of query answering and rewriting. We also describe some background material on relational databases, query languages, incomplete data, complexity theory, and automata theory (that will be required in the study of XML data exchange).

Part Two deals with exchanging relational data. We start by looking at the problem of checking if solutions, or possible target instances, exist. In general, the problem may even be undecidable, so we look at restrictions on schema mappings to guarantee not only

decidability but also tractability of the problem of building solutions. Under one restriction, called weak acyclicity, particularly nice solutions can be constructed efficiently. These are called universal solutions, and they are particularly well suited for query answering in data exchange. It turns out that a given source may have many targets compatible with it, and thus we use the semantics of certain answers, i.e., answers true in all compatible targets. It is those answers that can be efficiently found in universal solutions. Universal solutions themselves are not unique, and we look at two types of these, the canonical universal solution, and the core, that have particularly nice properties. We also look at alternative ways of defining the semantics of query answering in data exchange.

Part Three deals with exchanging XML data. It mimics the developments of Part Two, but there are crucial differences between XML and relations. In particular, the complexity of many basic tasks increases in the XML case, and one needs different types of restrictions for keeping the complexity manageable. We identify those, particularly by placing restrictions on schemas, as it is their complexity that affects data exchange problems most. We also look at answering two types of queries: XML-to-relations, and XML-to-XML. Finally, we show how to perform XML data exchange tasks using relational data exchange engines.

Part Four deals with metadata management, i.e., handling schema mappings themselves. We deal with their static analysis, in particular, the consistency (or satisfiability) problem and the simplification problem. We study schema evolution described by means of operations on mappings. Two key operations one needs are composition of mappings and inverting mappings, and we provide a detailed study of both.

Each part of the book comes with a summary, bibliographic comments, and exercises.

A much shorter draft of this book was published in the Morgan & Claypool Synthesis series under the title *"Relational and XML Data Exchange"* in 2010. While working on that short version, and on the full draft, as well as on papers that are reflected in this book, we benefited from comments and critical remarks from our colleagues. We would like to thank Shunichi Amano, Mikołaj Bojańczyk, Rada Chirkova, Wojtek Czerwiński, Claire David, Ronald Fagin, Wenfei Fan, Amélie Gheerbrant, Andre Hernich, Phokion Kolaitis, Maurizio Lenzerini, Katja Losemann, Wim Martens, Jorge Pérez, Juan Reutter, Cristian Riveros, Miguel Romero, Nicole Schweikardt, Thomas Schwentick, and Cristina Sirangelo. We are also grateful to Tamer Özsu and Diane Cerra for convincing us to write the short Morgan & Claypool version of the book, and to David Tranah at Cambridge University Press for persuading us to turn it into a proper book, and for his patience and assistance.

Santiago, Edinburgh, Warsaw M.A., P.B., L.L., F.M.

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PART ONE

GETTING STARTED

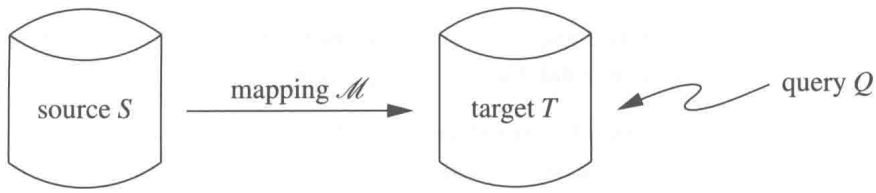
1

Data exchange by example

Data exchange is the problem of finding an instance of a target schema, given an instance of a source schema and a specification of the relationship between the source and the target. Such a target instance should correctly represent information from the source instance under the constraints imposed by the target schema, and should allow one to evaluate queries on the target instance in a way that is semantically consistent with the source data.

Data exchange is an old problem that re-emerged as an active research topic recently due to the increased need for exchange of data in various formats, often in e-business applications.

The general setting of data exchange is this:



We have fixed source and target schemas, an instance S of the source schema, and a mapping $\mathcal{M}$ that specifies the relationship between the source and the target schemas. The goal is to construct an instance T of the target schema, based on the source and the mapping, and answer queries against the target data in a way consistent with the source data.

The goal of this introductory chapter is to make precise some of the key notions of data exchange: schema mappings, solutions, source-to-target dependencies, and certain answers. We do it by means of an example we present in the next section.

1.1 A data exchange example

Suppose we want to create a database containing three relations:

- `ROUTES(flight#,source,destination)`

  This relation has information about routes served by several airlines: it has a `flight#` attribute (e.g., AF406 or KLM1276), as well as `source` and `destination` attributes (e.g., Paris and Santiago for AF406).

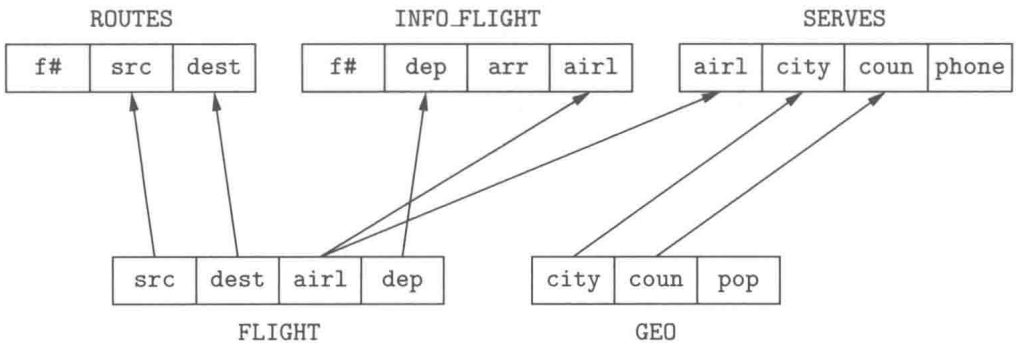


Figure 1.1 Schema mapping: a simple graphical representation

- `INFO_FLIGHT(flight#,departure_time,arrival_time,airline)`
  This relation provides additional information about the flight: departure and arrival times, as well as the name of an airline.
- `SERVES(airline,city,country,phone)`
  This relation has information about cities served by airlines: for example, it may have a tuple (*AirFrance*, *Santiago*, *Chile*, *5550000*), indicating that Air France serves Santiago, Chile, and its office there can be reached at 555-0000.

We do not start from scratch: there is a source database available from which we can transfer information. This source database has two relations:

- `FLIGHT(source,destination,airline,departure)`
  This relation contains information about flights, although not all the information needed in the target. We only have source, destination, and airline (but no flight number), and departure time (but no arrival time).
- `GEO(city,country,population)`
  This relation has some basic geographical information: cities, countries where they are located, and their population.

As the first step of moving the data from the source database into our target, we have to specify a *schema mapping*, a set of relationships between the two schemas. We can start with a simple graphical representation of such a mapping shown in Figure 1.1. The arrows in such a graphical representation show the relationship between attributes in different schemas.

But simple connections between attributes are not enough. For example, when we create records in `ROUTES` and `INFO_FLIGHT` based on a record in `FLIGHT`, we need to ensure that the values of the `flight#` attribute (abbreviated as `f#` in the figure) are the same. This is indicated by a curved line connecting these attributes. Likewise, when we populate table `SERVES`, we only want to include cities which appear in table `FLIGHT` – this is indicated by the line connecting attributes in tables `GEO` and `FLIGHT`.

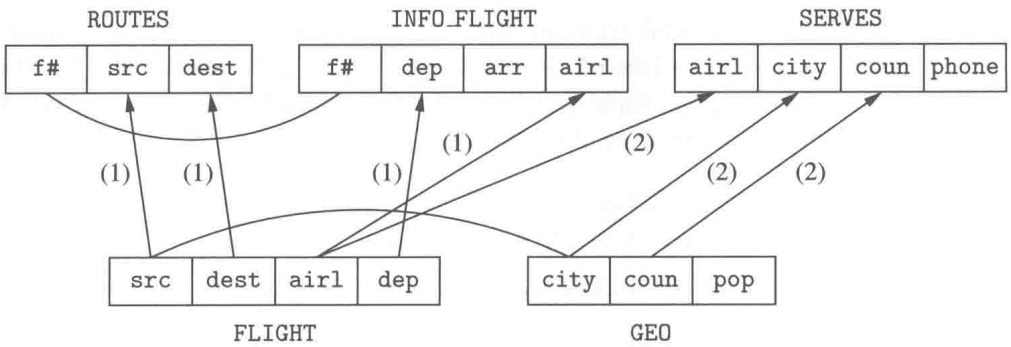


Figure 1.2 Schema mapping: a proper graphical representation

Furthermore, there are several *rules* in a mapping that help us populate the target database. In this example, we can distinguish two rules. One uses table FLIGHT to populate ROUTES and INFO_FLIGHT, and the other uses both FLIGHT and GEO to populate SERVES. So in addition we annotate arrows with names or numbers of rules that they are used in. Such a revised representation is shown in Figure 1.2.

While it might be easy for someone understanding source and target schemas to produce a graphical representation of the mapping, we need to translate it into a formal specification. Let us look at the first rule which says:

whenever we have a tuple (src,dest,airl,dep) *in relation* FLIGHT, *we must have a tuple in* ROUTES *that has* src *and* dest *as the values of the second and the third attributes, and a tuple in* INFO_FLIGHT *that has* dep *and* airl *as the second and the fourth attributes.*

Formally, this can be written as:

$$\texttt{FLIGHT(src,dest,airl,dep)} \longrightarrow \texttt{ROUTES(\_,src,dest), INFO\_FLIGHT(\_,dep,\_,airl).}$$

This is not fully satisfactory: indeed, as we lose information that the flight numbers must be the same; hence, we need to explicitly mention the names of all the variables, and produce the following rule:

$$\texttt{FLIGHT(src,dest,airl,dep)} \longrightarrow \texttt{ROUTES(f\#,src,dest), INFO\_FLIGHT(f\#,dep,arr,airl).}$$

What is the meaning of such a rule? In particular, what are those variables that appear in the target specification without being mentioned in the source part? What the mapping says is that values for these variables must *exist* in the target, in other words, the following must be satisfied:

$$\texttt{FLIGHT(src,dest,airl,dep)} \longrightarrow \exists \texttt{f\#}\, \exists \texttt{arr}\, \big(\texttt{ROUTES(f\#,src,dest)} \wedge \texttt{INFO\_FLIGHT(f\#,dep,arr,airl)} \big).$$