A View-based Programmable Architecture for Controlling and Integrating Decentralized Data

[Vision Paper]

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ABSTRACT

The view and the view update are known mechanism for controlling access of data and for integrating data of different schemas. Despite intensive and long research on them in both the database community and the programming language community, we are facing difficulties to use them in practice. The main reason is that we are lacking of control over the view update strategy to deal with inherited ambiguity of view update for a given view.

This vision paper aims to provide a new language-based approach to controlling and integrating decentralized data based on the view, and establish a software foundation for systematic construction of such data management systems. Our key observation is that a view should be defined through a view update strategy rather than a query. In other words, the view definition should be extracted from the view update strategy, which is in sharp contrast to the traditional approaches where the view update strategy is derived from the view definition.

In this paper, we present the first programmable architecture with a declarative language for specifying update strategies over views, whose unique view definition can be automatically derived, and show how it can be effectively used to control data access, integrate data generally allowing coexistence of GAV (global as view) and LAV (local as view), and perform both analysis and updates on the integrated data. We demonstrate its usefulness through development of a privacy-preserving ride-sharing alliance system, discuss its application scope, and highlight future challenges.

1. INTRODUCTION

Along with the continuous evolvement of data management systems for the new market requirements, centralized systems, which had often produced huge and monolithic databases, have been replaced by decentralized systems in which data are maintained in different sites with autonomous storage and computation capabilities. The owner of the data stored on a site may choose to show what information should be exposed and how its information should be updated by other systems. On the other hand, the systems would like to integrate data from different sites and perform analysis and update on the integrated data. The goal of this vision paper is to combine the advanced technologies developed in both the database community and the programming language community to establish software foundations to control and integrate these distributed decentralized data.

View update problem in DB

View plays an important role in controlling access of data and for integrating data of different schemas since it was first introduced by Codd about four decades ago. It is a relation derived from base relations, which is helpful to describe dependencies between relations and achieve database security within an authorization framework. Deeply associated with view is the classic view update problem: given a view defined by a query over base relations, show how to systematically reflect the changes made to the view as updates to the original base relations. Put it more concretely, given that $s$ represents a database state, $Q$ is a view definition, $Q(s)$ represents the view state from $s$, and $u$ represents the update operation issued to $Q(s)$, the view update problem is defined as finding a translation $T$ of $u$ such that the following commutative diagram holds.

$$
\begin{array}{c}
S & \xrightarrow{Q} & u' \\
\downarrow T(u) & & \downarrow u \\
S' & \xrightarrow{Q} & u'
\end{array}
$$

Despite a long and intensive study of the view updating in the database community, as discussed in, there are few really practical systems that can fully support view updating. It is essentially impossible to obtain a unique solution to a view update, because of potentially many incomparable strategies to reflect a view update. This calls for a general method to solve a fundamental tension between expressiveness and realizability in the view update problem. The richer language we use for defining views, the more difficult it becomes to find corresponding
functions to reflect the updates on the view to that on the base relations.

**Bidirectional transformation (BX) in PL**

To deal with this tension, many researchers in the programming language community have been attracted to generalize the concept of the view update problem to be a general synchronization problem [11][59], and designed various domain specific languages [15][62][17][6][27] to support so-called bidirectional transformation, which generalizes the manipulation of data from relations to other data types, and allows views to be materialized.

A bidirectional transformation (BX) consists of a pair of transformations:

![Diagram](image)

Here, the **forward** transformation \( \text{get}(s) \) is used to produce a target view \( v \) from a source \( s \), while the **putback** transformation \( \text{put}(s, v) \) is used to reflect updates on the view \( v \) to the source \( s \). These two transformations should be well-behaved in the sense that they satisfy the following round-tripping laws.

\[
\begin{align*}
\text{put}(s, \text{get}(s)) &= s & \text{GETPUT} \\
\text{get}(\text{put}(s, v)) &= v & \text{PUTGET}
\end{align*}
\]

The GETPUT property requires that no changing on the view shall be reflected as no changing on the source, while the PUTGET property requires all changes in the view to be completely reflected to the source so that the changed view can be computed again by applying the forward transformation to the updated source. Exact correspondence between the notion of well-behavedness in BX and the properties on view updates such as translation of those under a constant complement [5][12], has been extensively studied in [55].

It has been demonstrated in [5] that this language-based approach is useful to help solving the view update problem with a bidirectional query language, in which every expression can be interpreted forwardly as a view definition and backwardly as an update strategy.

One appealing feature of this language-based approach is its powerful type system, which includes record-level predicates and functional dependencies and can fully guarantee that update strategies are well-behaved. However, this solution is not that satisfactory, because it still cannot solve the issues of ambiguity of update strategies for a given view definition.

**Problem: lack of effective control of update strategy**

The main difficulty in using these techniques to control and integrate distributed decentralized data lies in the inherent ambiguity of the update strategy for a given query or a forward transformation. The problem is that we are lacking of effective way of controlling over the update strategy (or the putback transformation); it would be awkward and counter-intuitive to obtain our intended update strategy by changing the view definition that is under our control, when the view definition becomes complicated.

We have been taken it for granted that a view should be defined by a query and that a sound and intended update strategy should be automatically derived even if it is known that automatic derivation of an intended update strategy is generally impossible [38]. Now it is time to consider seriously the following two fundamental questions: (1) Must views be defined by queries? and (2) Must update strategies be automatically derived?

**Our vision: a programmable architecture**

This vision paper aims to provide a new language-based approach to controlling and integrating decentralized data based on the view, and establish a software foundation for systematic construction of such data management systems. Our key observation is:

> A view should be defined through a view update strategy to the base relations rather than a query from them.

This new perspective is in sharp contrast to the traditional approaches, and it actually gives an answer to the above two questions: a view is not necessary to be defined as a query, and an update strategy with human insight should be definable.

This vision stems from the recent work on the putback-based approach [31][17][11][40] to bi-directional programming. The key idea is that although there are many puts that can correspond to a given get, there is at most one get that can correspond to a given put, and such get can be derived from put. In other words in terms of view and view update, we have that

for a view definition and a view update strategy, while there may be many view update strategies for a given view definition, there is a unique view definition (if it exists) that corresponds to a view update strategy and this view definition can be derived.

This new perspective on view implies that we should design a language for describing view update strategies and treat the view definition as side-effect of the view update strategy. Following this line, we have designed BiGUL [41][40], a tiny putback-based BX language to support programming putback functions declaratively while automatically deriving the corresponding unique forward transformation. It is interesting to investigate how to extend BiGUL to describe update strategies on relations.

Our main technical contributions can be summarized as follows.

- We present the first language for specifying update strategies over views on base relations, whose unique view definition can be automatically derived. We demonstrate how it is effectively used to control data access, to integrate data generally allowing coexistence of GAV (global as view) and LAV (local as view) [14], and to perform both analysis and updates on the integrated data.
- We propose a novel view-based software architecture for systematic construction of a management system for controlling and integrating decentralized data. We highlight how this higher-level architecture can be implemented with PostgreSQL, where updates can be
incrementally propagated between the view and the
base relations and the well-behavedness in the higher-
level architecture can be well preserved.

- We demonstrate and validate this new approach
through development of an application of a ride-sharing
alliance system, where we can systematically obtain a
robust implementation of the system in PostgreSQL,
based on our view-based programmable architecture.
The prototype implementation is available online.

The organization of the rest of the paper is as follows. We
start with an overview of putback-based BX, the underlying
foundation of this paper, in Section 2 and give a motivation
example of a ride-sharing alliance system in Section 3. We
then propose our view-based programmable architecture in
Section 4, present our putback-based language for specifying
view update strategies in Section 5, and discuss its imple-
mentation in Section 6. We discuss the application scope,
challenges, and the evaluation criteria in Section 7, and give
remarks on related work in Section 8. Finally, we conclude
the paper in Section 9.

2. FOUNDATION: PUTBACK-BASED BX

As discussed in the introduction, lots of work \[18, 8, 7,
28, 22, 49, 61, 27\] on BX has been devoted to the “get-based
approach, allowing users to write the forward transformation
get and deriving a suitable putback transformation. While
the get-based approach is friendly, a get function may not
be injective, so there may exist many possible functions that
can be combined with it to form a BX and there is no way
to control the choice of put through the change of get. This
ambiguity of put is what makes bidirectional programming
challenging and unpredictable in practice.

In contrast to the get-based approach, the putback-based
approach allows users to write the backward transformation
put and derives a suitable get function that can be paired with put
to form a bidirectional transformation if it exists. Interestingly,
while get usually loses information when mapping from a
source to a view, put must preserve information when putting
back from the view to the source, according to the PutGet
property.

In the following, we recap the two important facts in
\[31\], showing that “putback” is the essence of bidirectional
programming. The first fact is that, for a put, there exists
at most one get that can form a BX with it. This is in sharp
contrast to get-based bidirectional programming, where many
puts may be paired with a get to form a BX.

**Lemma 2.1 (Uniqueness of get).** Given a put function,
there exists at most one get function that forms a
well-behaved BX.

The second fact is that it is possible to check validity of put
in the sense that there is a get that can be paired with put
to form a BX. The following are two important properties
on put.

- The first, that we call view determination, says that
  equivalence of updated sources produced by a put
  implies equivalence of views that are put back.

\[
\forall s, s', v, v'. \text{ put}(s, v) = \text{ put}(s', v') \Rightarrow v = v'
\]

**ViewDetermination**

- The second, that we call source stability, denotes a
  slightly stronger notion of surjectivity for every source:

\[
\forall s, \exists v. \text{ put}(s, v) = s \quad \text{SourceStability}
\]

Actually, these two properties together provide an equivalent
characterization of the validity of put.

**Theorem 2.2.** A put function is valid if and only if it
satisfies the ViewDetermination and SourceStability
properties.

**BigUL** \[41, 40\] is a tiny putback-based bidirectional
language, which grew out of the work \[53, 54\]. In this paper,
we will design a new bidirectional relational update language
based on the idea of BigUL.

3. RUNNING EXAMPLE

To explain our programmable architecture and our im-
plementation concretely, we shall consider an example of a “privacy-preserving ride-sharing alliance system”. Being
simple, this example gives a good demonstration of the need
for controlling and integrating decentralized data.

Ride-sharing has become popular as an application which
allows a person other than professional taxi drivers to pro-
vide a car service using his/her privately owned vehicle. As
companies who want to enter into the ride-sharing market
increase, it is expected that “alliances” between companies
also increase. A ride-sharing alliance system receives requests
from passengers and matches each request to a vehicle belong-
ing to one of the companies. In this system, companies might
obtain more chances to have beneficial passengers, while pas-
sengers might have more choices of companies. This system
might consist of ride-sharing companies and a mediator
(a third party, trusted to some degree) who integrates and
analyzes the vehicle data of the companies. The following is
one of the possible scenarios.

1. A passenger sends a request to the ride-sharing alliance
system (mediator) to book a taxi.
2. The mediator analyzes the user request and shows a
candidate list of \(K\) taxis to the passenger.
3. The passenger chooses a taxi and attempts to book the
taxi.
4. The mediator sends the update request to the local
database of a company that maintains the selected taxi.
5. If the company accepts the update, the company sends
the ack of SUCCESS to the mediator.
6. Otherwise, the company sends the ack of FAIL. Back
to Step 2.

Meantime, it is important to control/protect the privacy
of passengers and drivers in ride-sharing. Because drivers
are not professionals, passengers might not disclose their
important locations to many drivers, and vice versa. In
the ride-sharing alliance system, “privacy-preserving” for
passengers and drivers should mean to reduce the number of
companies which know the precise location of a passenger
and the number of vehicles whose precise locations are known
to the mediator. Previous researches about privacy-preserving
ride-sharing \[3, 22, 60\] have not considered such a system.
We present a solution in this paper as a demonstration of
our proposal.

\[1\] https://github.com/hiroyukikato/DataIntegration
The core parts in this programmable architecture are two BXs that are used in the data controller and in the data integrator respectively. They play an important role in controlling and integrating the data. Note that the analysis and update that are conducted on the integrated view in the integrator is common in most database management systems, which analyze the data and update them accordingly.

To illustrate, we show below how these two BXs are programmed for our running example, but leave the details of our update language for describing these BXs in Section 4.

In the privacy-preserving ride-sharing alliance system, we first consider controlling data in each taxi company. Each taxi company as a data controller has its own database as $S_i$, from which only a small portion ($V_i$) is exported to the mediator for queries and updates, where updates are directly programmed as controlled data sharing (Section 5.2). For example, updates to $V_i$ are redirected to each relation ($R_{ij}$) through the language constructs to split relations vertically (column-wise) or horizontally (row-wise). Note that in both cases, queries to generate $V_i$ from $S_i$ are automatically derived from such programs (Section 5.4).

Next, we consider integration of decentralized data. Our update language for programming BX is able to program selective acceptance of the updates. Suppose the update strategy of the first company does not allow updates to area data of their vehicles. If that attribute is changed on $V_1$ (at the data controller), then the putback program rejects such updates. Such views ($V_1, \ldots, V_n$) are used for the mediator (as a data integrator) to form an integrated view that is used for requests for booking/picking-up taxis by the passengers (“users” in Figure 1). Updates to the integrated view may trigger the updates on each view of the taxi company. Such propagation can be programmed as in Section 5.3 to route updates using company’s ID. The updates are sent to the views of each company through the connectors. Some of such updates may not be acceptable, and such update strategies are programmed as mentioned above.

It is worth noting that our update language allows GAV and LAV to coexist seamlessly in this architecture, though our views are materialized while views in GAV and LAV are usually virtual. GAV corresponds to the query derived from the program in the data integrator because the derived query combines $V_1, \ldots, V_n$ to create the integrated view $I$. On the other hand, LAV in general is to create local databases from global database. Although the update language encodes propagation of updates on the integrated database to every database of the data controllers at once, such program can be considered as a composition of all LAVs. Suppose a new company (ID 3) joined the alliance. Then what the programmer needs to do is to add new part in the program of data integrator in a modular way to describe how updates to the rows exported from company 3 is propagated to the view of the company ($V_3$), and how such updates are propagated to the source ($S_3$). Parts of the integrator program for other companies, and other controller programs for companies 1 and 2 can remain intact, enjoying the benefit of LAV. Requirements here include ability to suppress creating materialized view as much as possible to prevent exporting sensitive data. We will discuss challenges here in Section 7.

The next section describes how the behaviors described above are programmed by our update language.

5. A BIDIRECTIONAL LANGUAGE FOR DESCRIBING UPDATE STRATEGIES

In this section, we explain our BX language for describing (view) update strategies, the core of our programmable architecture, demonstrate how it can be used to program
strategies for controlling and integrating data, and show how the corresponding query can be derived from an update program.

5.1 Overview of the Language

With the traditional approaches, a view definition is given as a query that constructs view tables from source tables. By contrast, with our approach the programmer writes an update program that takes source tables and (possibly changed) view tables as input, and manipulates them with the aim of putting all information of the view tables into the right places of the source tables. From this update program we can then automatically derive the corresponding well-behaved query, which is amenable to standard techniques like query optimization and rewriting.

Below we introduce an experimental relational update language, in which the kind of update program described above can be written. The language follows the now classic combinator-based design \[18, 8\], and consists of:

- atomic instructions (CHECK and UPDATE) that check the integrity of a view table or overwrite parts of a source table using information from a view table, and
- composite instructions (VSPLIT and HSPLIT) that split a view table either vertically or horizontally, and continue to execute further update instructions on the resulting smaller view tables and the source tables.

Instead of giving formal definitions, we will illustrate the use of the language with examples (two data controllers in Section 5.2 and a data integrator in Section 5.3), after which we will explain how query derivation, the distinguishing feature of the language, is realized (Section 5.4).

5.2 Programming Data Controllers

Suppose that a ride-sharing company maintains the following source table about its vehicles:

\[
\text{vehicles}(\text{vid}, \text{loc}, \text{rid})
\]

Recorded for each vehicle are a unique vehicle identifier (vid, which is underlined to indicate that it is the primary key of the table), its current location (loc), and a request id (rid). For privacy reasons, when sharing vehicle information with the mediator, the company wishes to show only an approximate area where a vehicle is, rather than the precise location. The company therefore also maintains another source table mapping locations to areas:

\[
\text{area_map}(\text{loc}, \text{area})
\]

The view exposed to the mediator has the following schema:

\[
\text{peer1_public}
\]

\[
(\text{vehicle_id}, \text{current_area}, \text{request_id})
\]

which contains only approximate areas the vehicles are in. Our task here is to program a data controller that synchronizes this view table and the source tables.

In our approach, to establish the relationship between the source tables (\text{vehicles} and \text{area_map}) and the view table (\text{peer1_public}), we should describe an update strategy, that is, how view information should be used to update the sources. In particular, with an update strategy we can control what view information can be changed. For this example, we might allow the mediator to change only \text{request_ids} but not \text{vehicle_ids} and \text{current_areas}. Our strategy is therefore updating the \text{rid} attribute of \text{vehicles} while checking whether other information in the view (\text{vehicle ids} and \text{current areas}) is intact; if not, we regard the view as invalid and reject the update.

The above strategy is programmed in our language as follows:

\[
\text{VSPLIT VIEW peer1_public WITH}
\]

\[
\text{vehicle_id, request_id} \{
\text{UPDATE} \ \text{vid}, \ \text{rid}
\IN \text{SOURCE} \ \text{vehicles}
\WITH \ \text{vehicle_id}, \ \text{request_id}
\IN \text{VIEW} \ \text{peer1_public}
\}
\]

\[
\text{vehicle_id, current_area} \{
\ \text{CHECK VIEW peer1_public EQUALS}
\ \text{SELECT} \ \text{vid AS vehicle_id,}
\ \text{area AS current_area}
\ \text{FROM} \ \text{vehicles, area_map}
\ \text{WHERE} \ \text{vehicles.loc = area_map.loc;}
\}
\]

We vertically split (i.e., project) \text{peer1_public} into two tables, the first one consisting of the two attributes \text{vehicle_id} and \text{request_id}, and the second one the two attributes \text{vehicle_id} and \text{current_area}. The two projected tables, still named \text{peer1_public}, are used respectively in the two parallel updates specified in the blocks enclosed in curly brackets:

- In the first block, we update \text{vid} and \text{rid} in \text{vehicles} with the corresponding attributes in \text{peer1_public}. This is done by matching records in the source and view tables by their keys, i.e., \text{vid} and \text{vehicle_id}, replacing \text{rid} with \text{request_id}, and keeping the unmentioned attribute \text{loc} unchanged.

- In the second block, we make sure that the mediator does not tamper with the attributes \text{vehicle_id} and \text{current_area} in \text{peer1_public} by checking whether \text{peer1_public} (which, in this block, has only the two attributes) is equal to the result of a query that extracts the source information that should be kept unchanged and translates locations to areas. The whole update is rejected if this check fails.

What is interesting is that from the update program we can automatically extract the corresponding well-behaved query, which is equivalent to:

\[
\text{SELECT} \ \text{vid AS vehicle_id, area AS current_area,}
\ \text{rid AS request_id}
\ \text{INTO} \ \text{peer1_public}
\ \text{FROM} \ \text{vehicles, area_map}
\ \text{WHERE} \ \text{vehicles.loc = area_map.loc;}
\]

To show a different data controller, suppose that another company maintains occupied and unoccupied vehicles in two separate tables:

\[
\text{occupied_vehicles(vid, area, rid)}
\]

\[
\text{unoccupied_vehicles(vid, area)}
\]

There is no request id for an unoccupied vehicle, so we omit the \text{rid} attribute in \text{unoccupied_vehicles}; also, unlike the first company, this company stores only the approximate
areas the vehicles are in. The view exposed to the mediator is the same as the first company’s except for the table name:

```plaintext
table peer2_public
  (vehicle_id, current_area, request_id)
```

The update strategy is specified as follows:

```plaintext
HSPLIT VIEW peer2_public ON request_id
  null {
    UPDATE vid, area
    IN SOURCE unoccupied_vehicles
    WITH vehicle_id, current_area
    IN VIEW peer2_public
  }
  OTHERWISE {
    UPDATE vid, area, rid
    IN SOURCE occupied_vehicles
    WITH vehicle_id, current_area, request_id
    IN VIEW peer2_public
  }
```

This time we horizontally split (i.e., select) `peer2_public` into two tables based on the `request_id` attribute: the first table consists of all the records whose `request_id` is null, and all other records are collected in the second table. The two tables (still named `peer2_public`) are then used to update `unoccupied_vehicles` and `occupied_vehicles` respectively. Again from this program we can derive the corresponding well-behaved query:

```plaintext
SELECT *
INTO peer2_public
FROM SELECT vid AS vehicle_id,
           area AS current_area,
           null AS request_id
FROM unoccupied_vehicles
UNION
SELECT vid AS vehicle_id,
       area AS current_area,
       rid AS request_id
FROM occupied_vehicles;

5.3 Programming Data Integrators

Instead of the two tables `peer1_public` and `peer2_public` provided by the ride-sharing companies, the mediator prefers to work on a single table:

```plaintext
all_vehicles(company_id, vehicle_id,
current_area, request_id)
```

Synchronization between the table `all_vehicles` and the two tables `peer1_public` and `peer2_public` is performed by a data integrator, which, like data controllers, can be programmed with our language by specifying how to put `all_vehicles` into `peer1_public` and `peer2_public`. The program is similar to the one for the second company’s data controller: we perform a horizontal split on `company_id` and put the resulting tables into either `peer1_public` or `peer2_public`.

```plaintext
HSPLIT VIEW all_vehicles ON company_id
  1 {
    UPDATE vehicle_id, current_area,
        request_id
    IN SOURCE peer1_public
    WITH vehicle_id, current_area,
        request_id
    IN VIEW all_vehicles
  }
  2 {
    UPDATE vehicle_id, current_area,
        request_id
    IN SOURCE peer2_public
    WITH vehicle_id, current_area,
        request_id
    IN VIEW all_vehicles
  }
```

And the derived query is:

```plaintext
SELECT *
INTO all_vehicles
FROM SELECT *, 1 AS company_id
FROM peer1_public
UNION
SELECT *, 2 AS company_id
FROM peer2_public;

5.4 Query Derivation

The precise semantics of the language is intricate and requires careful design (by imposing syntactic and semantic constraints) to guarantee well-behavedness like what Bohannon et al. did with their “relational lenses” [8], but we will not go into the details here. (See Section 8 for a discussion of Bohannon et al.’s work.) Instead, we will only explain the language’s distinguishing feature: the mechanism of query derivation. Each statement — CHECK, UPDATE, VSPLIT, or HSPLIT — corresponds to a kind of query, and the correspondence, i.e., translation from update programs to queries, can be described syntactically.

The simplest case is a CHECK statement:

```plaintext
CHECK VIEW viewTable EQUALS srcQuery
```

whose corresponding query is exactly `srcQuery`. A slightly more interesting case is an UPDATE statement:

```plaintext
UPDATE srcAttrs IN SOURCE srcTable
WITH viewAttrs IN VIEW viewTable
```

which is translated into projection and attribute renaming:

```plaintext
SELECT srcAttrs AS viewAttrs
INTO viewTable
FROM srcTable;
```

When it comes to composite statements, i.e., VSPLIT and HSPLIT, the general plan is to derive queries from the blocks and then assemble the results of the queries. For a VSPLIT statement:

```plaintext
VSPLIT VIEW viewTable WITH
  ViewAttrs1 {p1}
  ...
  ViewAttrs_n {pn}
```
we translate it into a join:

\[
\text{query derived from } p_1, \\
\text{where all occurrences of 'viewTable' are replaced with an unused table name 'tmpTable' }_1; \\
\ldots \\
\text{query derived from } p_n, \\
\text{where all occurrences of 'viewTable' are replaced with an unused table name 'tmpTable' }_n;
\]

\[
\text{SELECT } \bigcup_i \text{viewAttrs}_i \\
\text{INTO } \text{viewTable} \\
\text{FROM } \text{tmpTable}_1, \ldots, \text{tmpTable}_n \\
\text{WHERE } \text{tmpTable}_i, attr = \text{tmpTable}_j, attr \\
\text{for all } i \neq j \text{ and } attr \in \text{viewAttrs}_i \cap \text{viewAttrs}_j; \\
\]

And for an HSPLIT statement:

\[
\text{HSPLIT VIEW } \text{viewTable ON } \text{viewAttr} \\
\text{value}_1 \{ p_1 \} \\
\ldots \\
\text{OTHERWISE } \{ p_n \}
\]

we translate it into a union:

\[
\text{query derived from } p_1, \\
\text{where all occurrences of 'viewTable' are replaced with an unused table name 'tmpTable' }_1; \\
\ldots \\
\text{query derived from } p_n, \\
\text{where all occurrences of 'viewTable' are replaced with an unused table name 'tmpTable' }_n;
\]

\[
\text{SELECT } * \\
\text{INTO } \text{viewTable} \\
\text{FROM SELECT } *, \text{value}_1 \text{ AS viewAttr} \\
\text{FROM } \text{tmpTable}_1 \\
\ldots \\
\text{UNION} \\
\text{SELECT } * \\
\text{FROM } \text{tmpTable}_n;
\]

We deliberately keep the language simple so that we can explain its query derivation mechanism in a straightforward manner. In general, query derivation will be much more complex for more expressive update languages (e.g., BiFluX [54]).

6. IMPLEMENTATION IN POSTGRESQL

In this section, we briefly explain how the programmable architecture given in Section 4 can be implemented in a conventional DBMS, PostgreSQL, and concretely demonstrate how the ride-sharing alliance system is actually implemented with PostgreSQL.

6.1 Basic Ideas

As stated in Section 4, our programmable architecture has three parts, namely, data controller, data integrator, and data connector. The basic ideas for implementing them are described below.

1. Data controller.

Each data controller uses materialized views (i.e., \(V_1, \ldots, V_n\) in the lower part of Figure 1) to export a part of its own, original data to others. The materialized views are derived by the BX (i.e., predefined update strategy and the corresponding view definition) established within the data controller. In order to control the exported data, an update on the materialized views is interpreted first by the update strategy (and hence, by the data provider). The update is then rewritten and propagated to the source tables of the views only when the given update is acceptable to the update strategy.

2. Data integrator.

The data integrator keeps copies (i.e., \(V_1, \ldots, V_n\) in the upper part of Figure 1) of the materialized views of data controllers. The integrated view (i.e., \(I\) in Figure 1) is derived and materialized from those copies by BX. An update on the integrated view is rewritten to updates on the copies, and then the updates are propagated to the materialized views at the data controllers.

3. Data connector.

The copies at the data integrator are synchronized with the materialized views at the data controllers, and vice versa. This part is not difficult to implement by utilizing PostgreSQL’s functionalities such as Foreign Data Wrappers (FDW for short).

From the perspective of implementation, the key parts are data controller and data integrator because they contain BX inside. The detail of the implementation, especially how to realize the query rewriting and propagation by BX, will be explained in Section 6.2. After that, in Section 6.3 it is demonstrated that the three parts can be implemented with PostgreSQL through the ride-sharing alliance example.

6.2 Implementing BX in PostgreSQL

In this subsection, we briefly describes an important implementation issue that how the BX can be systematically implemented in PostgreSQL. We use triggers, which can be used to define functions based on ECA (Event, Condition and Action)-rules. As a language for defining trigger functions, a PostgreSQL-dialect of PL/SQL called PL/pgSQL has enough expressive power to implement the update strategy. As described above, there are two kinds of BX in the programmable architecture. One is established in the data controller, the other is established in the data integrator. For each BX (a derived get and a predefined put), bidirectional update propagation can be realized by preparing two triggers, one is defined on views and the other is defined on tables, which compose the views. Note that one may implement a bidirectional update propagation by preparing two trigger functions, independently. However, in such implementations, the important property, the round-trip property shown in the introduction, can not be guaranteed. Instead, we define two trigger functions satisfying the property by translating through the well-behaved BX (a get and a put). Note also that we need to avoid falling in infinite loops by pulling the triggers in both sides.

Since both the views of self-controllable data in the data controller and integrated views in data integrator are materialized, both an incremental version of view maintenance for get and an incremental version of put with respect to the updates are needed to implement the updates propagation in trigger functions to reflect both updates on sources and views efficiently. So, the incremental version of view maintenance for get with respect to an update on a source specifies...
how to reflect an update to the materialized view when the update is executed to source data. Whereas, the incremental version of put specifies how to reflect an update to the source data when the update is executed to a view. In other words, for given a source database $S$, a view definition get and an update $u$ on the source $S$, an incremental version of view maintenance for get with respect to $u$ denoted by $u'$ satisfies the following equation:

$$
get(w(S)) = w'(get(S))
$$

Also, for given a materialized version $V$ of two steps:

Section 5.2. For implementing a get and an update strategy for put with respect to $u$ denoted by $u'$ satisfies the following equation:

$$
put(S, u(V)) = u'(V)
$$

Note that we can apply the existing work \[2\] and \[29\] to obtain an incremental view maintenance for get and an incremental update strategy for put, respectively.

Now, we show, for given a BX (a get and a put), the whole steps to implement two trigger functions, one is for a get and the other is for a put by using the examples shown in Section 5.2. For implementing a get, we use the following two steps:

(g1) Deriving an incremental version of view maintenance.

An incremental version of view maintenance for get with respect to an update on a source can be obtained based on a static analysis \[2\]. For example, when the following insertion $w$ is executed to $vehicles$ shown in Section 5.2:

$$
\begin{align*}
&\text{INSERT INTO } vehicles \\
&\text{VALUES (new_vid, new_loc, new_rid)}
\end{align*}
$$

the following $u'$ can be obtained from the view definition get derived from the update strategy for $peer1_public$ shown in Section 5.2:

$$
\begin{align*}
&\text{INSERT INTO } public_peer1 \\
&\text{SELECT new_vid, area, new_rid} \\
&\text{FROM area_map} \\
&\text{WHERE area_map.loc = new_loc}
\end{align*}
$$

(g2) Translating the incremental view maintenance into a trigger function.

For example, the above incremental version of view maintenance can be translated into the following pseudo code in trigger function defined on $vehicles$:

```sql
CREATE OR REPLACE FUNCTION 
vehicles()
RETURNS trigger AS $$
BEGIN
  IF TG_OP = 'INSERT' THEN
    INSERT INTO public_peer1
    SELECT new_vid, area, NEW.rid
    FROM area_map
    WHERE area_map.loc = New.loc;
  ELSE ... END IF;
RETURN NEW;
END;
$$ LANGUAGE plpgsql;
```

The above trigger function works that when an event of insertion to $vehicles$ is happened, the insertion of the incremental view maintenance to $public_peer1$ is also executed.

Similarly, for implementing a put, we use the following two steps:

(p1) Deriving an incremental version of an update strategy. An incremental version of $put$ with respect to an update on a view can be obtained based on a static analysis \[29\]. For example, when the following update $u$ is executed to $peer1_public$:

$$
\begin{align*}
&\text{UPDATE peer1_public} \\
&\text{SET request_id = new_id} \\
&\text{WHERE vehicle_id = id}
\end{align*}
$$

the following $u'$ can be obtained for a given update strategy shown in Section 5.2:

$$
\begin{align*}
&\text{UPDATE vehicle} \\
&\text{SET rid = new_rid} \\
&\text{WHERE vid = id}
\end{align*}
$$

(p2) Translating the incremental $put$ into a trigger function. For example, the above incremental version of update strategy can be translated into the following pseudo code in trigger function is defined on $peer1_public$:

```sql
CREATE OR REPLACE FUNCTION 
update_peer1_public()
RETURNS trigger AS $$
BEGIN
  IF TG_OP = 'UPDATE' THEN
    UPDATE vehicle
    SET rid = NEW.request_id
    WHERE vehicle_id = id;
  ELSE ... END IF;
RETURN NEW;
END;
$$ LANGUAGE plpgsql;
```

The above trigger function works that when an event of update on $public_peer1$ is happened, the update of the incremental $put$ on $vehicles$ is also executed.

6.3 Example: Implementation of Privacy-Preserving Ride-Sharing Alliance System

We explain the implementation details of the ride-sharing alliance system as described in Section 3. The system provides a data to book an appropriate taxi for a passenger. Figure 2 shows a framework for the system. The mediator integrates data from multiple taxi companies that manage their own databases whose schemes are different each other.

6.3.1 Implementing Basic Parts

To implement the framework of the system, we need to implement the basic parts (i.e., data controller, data integrator, and data connector in Section 6.1). In addition, we implement a function to analysis user requests.
**Data controller**

Each taxi company maintains their own database. To simplify the discussion, we assume two taxi companies use different schema as shown in Section 5. In each database, there are multiple tables and one materialized view (peer\textsubscript{i}.public). peer\textsubscript{i}.public is used to provide information from each company to the mediator. This view conceals the private information such as the precise locations of the vehicles.

Each database of a taxi company is self-controllable since it is managed only by the taxi company while peer\textsubscript{i}.public is used for exporting data to the mediator. Each table (such as vehicles table at provider 1) can be updated from outside only through the update of peer\textsubscript{i}.public. To this end, we use triggers provided described in Section 6.2. This trigger is executed at each provider (the lower part of Figure 2).

**Data integrator**

The mediator integrates the disclosed information on each peer as an integrated view all\textsubscript{vehicles}, and it provides data in a common schema for the analysis. all\textsubscript{vehicles} is created as a virtual view on the mediator by the query descried in Section 5.3. Since the mediator updates all\textsubscript{vehicles} for booking taxis, the update is propagated to the database at each peer. We have two triggers on mediator for updating all\textsubscript{vehicles} from provider 1 and peer\textsubscript{1}.public from the mediator are the following.

```sql
CREATE OR REPLACE FUNCTION update_peer1_public_mediator()
RETURNS TRIGGER
AS $$
BEGIN
  IF NEW.company_id = 1 THEN
    UPDATE peer1_public
    SET request_id=NEW.request_id
    WHERE vehicle_id=NEW.vehicle_id;
  ELSIF NEW.company_id = 2 THEN
    ... RETURN NEW;
  END;
END;
$$;
```

Both triggers are executed at the mediator (the upper part of Figure 2).

**Data connector**

The mediator and each provider are connected by FDW, and thus each peer\textsubscript{i}.public on the mediator is defined as a foreign table. The databases on the providers may not allow updating because a vehicle that is tried to be booked may be already booked by other passengers. For handling this case, each peer sends back error messages, and if the mediator receives the messages, it analyzes the passengers’ requests again.

### 6.3.2 Data Analysis on Mediator

The system analyzes the passenger request, and then shows a list of taxis to passengers. We describe how the mediator analyzes data on the integrated view. The system analyzes the benefits of taxi companies based on the time of the request and the locations of the start point, destination, and vehicles. For example, it lists \( K \) taxis with the highest benefits. A pseudocode to list \( K \) taxis is as follows:

```sql
FUNCTION candidate_taxis ( $\$
```

$$; CREATE OR REPLACE FUNCTION update_all_vehicles_on_peer1()
RETURNS TRIGGER
AS $$
BEGIN
  IF TG_OP = 'UPDATE' THEN
    UPDATE all_vehicles
    SET 1 AS company_id
    request_id=NEW.req_id
    current_area = NEW.current_area
    WHERE
    vehicle_id = NEW.vehicle_id
  END IF;
  RETURN NEW;
END;
$$;
```

```sql
FUNCTION candidate_taxis ( $\$
```

$$;
Fig. 1. The importance of personal data market for general scientific metadata is in different formats depending on the data owners and buyers. We expect the BX mechanism in our architecture plays an important role. In the domain of earth science, we generalize the dataset such as dataset name, dataset creator, abstract text, spatiotemporal information, keywords, and so on. Such metadata are in different formats depending on the target fields, and managed at each organization the data belong to. Therefore, we have many local databases for metadata management, which have their own update strategy and security policy.

With the growth of interdisciplinary data science, there are some systems for integrated management of scientific data and metadata. The systems like GCMD[5] and PANGAEA[3] accept scientific metadata of various earth science fields in their specified format, while the search systems of GEOSS[51] and DIAS[37] work as mediators to integrate scientific metadata from local databases. Note that the focus of these systems is providing search functions, and therefore analysis and updates on the integrated data are not well considered. Our architecture can be naturally applied to the management of scientific metadata, and for example, it will be useful for the curation on the integrated data.

7. DISCUSSION

In this section, we discuss important issues in our proposed programmable architecture, including the application scope (through two more interesting application examples), challenges in practical design and implementation of the architecture, and the evaluation criteria.

7.1 Potential Applications

7.1.1 Personal Data Market

A platform for personal data market is one of important potential applications of our programmable architecture (Fig. 1). The importance of personal data market for general and specific (e.g. geosocial) data is widely acknowledged. A number of related works has been emerging which include pricing, auction, and architecture.

To protect privacy, data owners should retain control over their own personal data and should have a right to specify a subset of data to be shipped to a marketplace. This scenario of personal data owners and marketplace nicely fits with our programmable architecture shown in Fig. 1. In this scenario of personal data market, data controllers and data integrator in Fig. 1 are regarded as data owners and marketplace, respectively. Data owners release a subset of their data as views $V_1, \ldots, V_n$. The marketmaker sells an integrated view $I$ to the buyer (which is represented as a user in Fig. 1).

Current studies in personal data market assume simple transactions without negotiation between data owners and buyers. However, we foresee transactions in practical personal data market are not straightforward in many cases because of its inherent complexity. The price which data owners ask is not a simple numeric value but might be a function of degree of privacy disclosure (which, among others, is measured by $\epsilon$ of differential privacy.) Meanwhile, buyers may offer bonus to data owners as an incentive to release personal data.

7.1.2 Management of Scientific Metadata

For the management of scientific data, the metadata plays an important role. In the domain of earth science, we generally make dataset-level metadata which describe the overview of the dataset such as dataset name, dataset creator, abstract text, spatiotemporal information, keywords, and so on. Such scientific metadata are in different formats depending on the target fields, and managed at each organization the data belong to. Therefore, we have many local databases for metadata management, which have their own update strategy and security policy.

With the growth of interdisciplinary data science, there are some systems for integrated management of scientific data and metadata. The systems like GCMD[5] and PANGAEA[3] accept scientific metadata of various earth science fields in their specified format, while the search systems of GEOSS[51] and DIAS[37] work as mediators to integrate scientific metadata from local databases. Note that the focus of these systems is providing search functions, and therefore analysis and updates on the integrated data are not well considered. Our architecture can be naturally applied to the management of scientific metadata, and for example, it will be useful for the curation on the integrated data.

7.2 Future Challenges

In the following, we highlight some important challenges in design and implementation of the programmable architecture, and show possible ways to tackle them.

7.2.1 Issues in Bidirectional Update Languages

The bidirectional relational update language in Section 5 serves to demonstrate possibility of designing a language to specify (well-behaved) view update strategies, from which the unique corresponding query can be automatically derived. This kind of framework has been studied in other settings for some years and recently established more convincingly as a plausible approach[40], but it has not been instantiated for relational databases. The future challenges on this language are as follows.

Language extension

The current language is rudimentary and not powerful enough for more sophisticated scenarios. Despite its simplicity, what underlies the language is a general-purpose update programming model (as opposed to a restrictive model that translates view modifications to source modifications using a hard-wired translation logic), and the language can eventually be extended with more programming constructs so that programmers can freely and fully customize their update strategies.

Well-behavedness of update strategies

Certainly not any view update strategy is well-behaved in the sense that there exists a query that can be paired with it to form a bidirectional transformation. We omit the discussion about how to validate the well-behavedness of an update strategy in our bidirectional relational update language, but as discussed in Section 2, we can follow the idea in[31] to design a static analysis algorithm to do this validation.

Efficient incrementalization of view-updating

Challenges in propagating updates through relational views include avoiding to use materialized views as much as possible. In current state of the art of relational lenses, although Bohannon et al.’s approach[7] has been incrementalized by Horn and Cheney[29, 30], their approach still requires querying source data to compute update translation. This is because some of the updates on the view may affect the

\begin{verbatim}
  u_pickup_location  int,
  ...
)
RETURNS TABLE (  
  u_company_id  int,
  u_vehicle_id  int,
  total_benefit  int
  ...)
)
ORDER BY
  total_benefit DESC
LIMIT K;
\end{verbatim}
original source database indirectly through functional dependency. We could reduce such query to source database by implementing query in a compositional way, and make a component query closer to the database selective enough so that backward execution of the subsequent queries may access only limited materialized view. In other words, we believe that the known push-down optimization can be considered not only for view computation but also for view updating.

### 7.2.2 Implementation Issues

We roughly show that the programmable architecture can be implemented over PostgreSQL in Section 6 and the future challenges are as follows.

#### Automatic translation

The core part of this translation from the higher-level description to the lower-level implementation over PostgreSQL is the translation of update strategies to a pair of triggers for propagating updates bidirectionally. This includes a systematic derivation queries from update strategies and an automatic incrementalization of both of them. Although theoretically all of them can be done, but it is a good engineering work in practice to implement the above efficiently.

**FDW and trigger functions**

Since we rely on PostgreSQL FDW and trigger functions for data synchronization among database servers, we share their benefits and limitations. In particular, the transaction is supported across/inside database servers. FDW supports nested transactions between local server and remote servers, so commits and aborts are synchronous between them. The triggers are designed to be executed in the same transaction of its main transaction. However, a major limitation is that distributed deadlock cannot be detected by FDW, so the applications that access to the databases are carefully designed to avoid distributed deadlock.

**Heterogeneous databases**

The current implementation uses PostgreSQL, but we can easily extend our system to use other relational database management systems. We should also support NoSQL databases (Apache HBase, Drill, MongoDB, etc), since they are widely used in various applications. The difficulty of using NoSQL as the data controller is that it does not support logical data model and SQL as a query language. It is our future work to support NoSQL so that our system can be applicable to more heterogeneous environment.

**View materialization**

Near real-time event streams are becoming a key feature of recent applications. For example, Twitter and Facebook allow users to create a personalized feed (timeline view) by selecting their friends to follow. The timeline view collects the latest posts of the friends in real-time. The ride-sharing alliance system needs to provide best matches between passengers and taxis based on their latest locations. To achieve efficient real-time services, we need to adaptively materialize views to improve the system performance. A typical approach is to use control table that contains hot data (users and/or taxis) to be dynamically materialized. Feeding

---

1. https://www.postgresql.org/docs/10/static/postgres-fdw.html

---

7.3 Successful Criteria

The output of the project would be a general software environment supporting people to develop a dependable system for controlling and integrating decentralized data in a systematic and productive way. To demonstrate the usefulness of the environment, we will show how to use it to develop some concrete systems such as those mentioned in this paper, and we would go even further to construct some specific software environments for productive development of some special but widely used systems such as health-care systems or publishing systems.

8. RELATED WORK

**Bidirectional transformation**

Relational lens is a linguistic approach to the view update problem for relational databases. It is based on the notion of lenses – originally proposed for trees – combinators equipped with well-behaved bidirectional semantics. In case of relational lenses, relational operators selection, projection and join are bidirectionalized while composition of them are achieved by the composition lens which preserves well-behavedness by a type system of lenses. A type of a relational lens specifies a domain (for a set of sources) and range (for a set of views). Types can also represent functional dependencies, so typing rule entails manipulating functional dependencies sometimes in non-trivial way, like decomposition. Bohannon et al.’s typing rules are highly declarative, for example, by including judgments of a particular functional dependencies to be satisfied by any input relation. Bohannon et al.’s technical report includes static manipulation of functional dependencies to facilitate such judgments. However, there are constraints imposed by Bohannon et al.’s approach and its programmability. The join lens requires that the join key functionally determines the entire attributes of the right relation. Additionally, predicates for the source relations should be independent from the output parts of the functional dependencies. As for programmability of Bohannon et al.’s approach, they can control how deletions of a tuple in the view reflect to deletions of a tuple in the source. However, it cannot depend on the source relation like our approach but just refers deleted tuples in the view.

Horn and Cheney incrementalized the relational lenses by providing their own putback semantics that takes, instead of states of updated views, set of tuples that are inserted or deleted in the views (called deltas) where modifications are represented by a pair of insertion of new tuple after modification and deletion of old tuple before modification. Their representation of updates are thus compact. They translate these deltas to source through compositions of lenses. Bohannon et al.’s updates are made explicit to achieve this translation, by per-tuple representations associated with functional dependencies needed for their adjustment, and manipulable representation of predicates in which occurrences of attribute names are replaced by an expression that would
calculate its updated value. That achieves efficient repre-
sentation of adjustments of attributes. Significant speedup
over state-based approach has been observed by the authors.
Since their approach is a natural extension of Bohannon et
al.’s, the adjustment of source tuples violating functional
dependencies requires access to source. However, different
from our general update language, they focus on incremental
semantics for the specific putback functions that are prede-
fined in the basic relational lenses. We should generalize
their incrementalization approach to deal with more general
putback functions in our update language.

One attempt has been made to design Brul [33], a putback-
based Haskell library for bidirectional transformations on
relations. It provides basic combinators for writing the put
function with flexible update strategies easily. Unlike our
bidirectional update language, Brul is a library which is not
as general as ours. In addition, it shows how a get semantics
can be given to a put program, but it does not show how an
explicit definition of get can be obtained.

**View updating**

To resolve the ambiguity problem in the view updating, Ma-
sunaga recently introduced the intention-based approach [47]
[48]. It shows that the user’s view update intention (update
strategy) sometimes can be guessed by checking the exten-
sion of each view update transformation candidate, which is
calculated using temporarily materialized views. Under
the intention-based approach, join views and Cartesian prod-
uct views became updatable in certain cases. However, this
"guess" does not guarantee that a unique update intention
can be obtained in general. We tackle this problem by let
people write their intention explicitly.

**Data integration**

The classical architecture of data integration is centralized.
That is, one mediator gathers all the distributed data, trans-
forms the data according to the schema mappings, and pro-
vides the uniform data to its users. On the other hand, de-
centralized data integration, or peer-to-peer data integra-
tion, has been focused on and many prototype systems have
been developed since the beginning of this century.

Piazza [25] [24] is one of the first projects on decentralized
data integration. The Piazza system is for integrating dis-
tributed XML documents without using global ontologies. It
provides query answering functionality based on the certain
answer semantics by rewriting given query. Updating XML
documents on peers is out of the scope.

Orchestra [32] [30] is a successor project of Piazza. This project
is motivated by the need for collaborative sharing of
scientific data, which are produced by independent re-
searchers without any global agreement. The novel concept
proposed by the project is referred to as collaborative data
sharing systems (CDSS for short). In CDSS, every peer can
independently import other peers’ data, modify the imported
data, merge the modified data with its original data, and
then publish the merged data to other peers. A peer can
update the data published by itself. Such an update is prop-
a gated to updates on its original data and the imported data.
Then, the new published data are imported again by other
peers. Hence, the view update problem between different
peers is out of the scope of this project. Moreover, in CDSS,
data inconsistency between different peers is positively al-
lowed because of the motivation, and therefore, transaction
processing over different peers is not realized.

The Hyperion project [39] [31] proposes an architecture of a
pair of database management system (PDBMS for short). A
PDBMS consists of three components: an interface to the
users, an ordinary DBMS, and a P2P layer, which is the
key component of a PDBMS. A P2P layer has the following
three functionalities: managing neighbor peer relationship,
query rewriting for answering queries, and enforcing data
consistency upon different peers. Because successive query
rewriting loses information of the original query, a framework
called GrouPeer [34] [33] was proposed to improve the quality
of answering queries. GrouPeer finds semantically similar
peers and makes them neighbors to avoid successive query
rewriting. In these frameworks, it is unclear whether updat-
ing data on other peers is possible. Even if this is the case,
controlling update strategy does not seem to be supported.

**Ride-sharing**

Research on ride-sharing has a long history. Refer to com-
prehensive surveys of ride-sharing for more details [20] [1].
On the other hand, there are a few researches about privacy-
-preserving ride-sharing. Aivojdi et al. [3] proposed a method
for computing pick-up and drop-off points for a driver and a
passenger without disclosing their precise locations by
employing a homomorphism encryption. Goel et al. [22] pro-
posed a method for matching drivers and passengers while
reducing the number of drivers and passengers who know
the precise locations of others by approximating location
information. They also employ a review system in order to
eliminate malicious drivers or passengers instead of prevent-
ing their attacks directly. Tong et al. [60] proposed a method
utilizing differential privacy which have been known as a
powerful technique for protecting privacy recently. These
methods do not consider a ride-sharing alliance which is dealt
with by our work.

9. CONCLUSION

In this vision paper, we have proposed a novel perspective
of views, which are defined using view update strategies
rather than queries. This perspective stems from the studies
of bidirectional transformations within the programming lan-
guage community, in particular the insight that well-behaved
queries are uniquely determined by, and can be derived from,
view update strategies. Based on this insight, we have de-
dsigned, for relational databases, a new language for defining
views with update strategies, from which the correspond-
ing view queries can be automatically derived. With this
relational update language as the core, we have presented a
new view-based programmable architecture for data sharing,
integration, and analysis. Within this architecture, system
designers can describe the appropriate data sharing and in-
tegrating policies by programming them in the relational
update language, rather than having to rely on some hard-
wired and often limited view-updating logic derived from
query-based view definitions. As an initial validation of
the approach, we have implemented a prototype of a ride-sharing
alliance system following the architecture. We believe that it
is worth reporting as early as possible the new perspective
of views and the view-based programmable data management
architecture arising from the new perspective, so that re-
searchers in databases and programming languages can start
working together to explore this promising direction.
10. REFERENCES

[1] N. Agatz, A. Erera, M. Savelsbergh, and X. Wang. Optimization for dynamic ride-sharing: A review. *European Journal of Operational Research*, 223(2):295–303, 2012.

[2] Y. Ahmad, O. Kennedy, C. Koch, and M. Nikolic. DBToaster: Higher-order delta processing for dynamic, frequently fresh views. *PVLDB*, 5(10):968–979, 2012.

[3] U. M. Aivodji, S. Gambs, M.-J. Huguet, and M.-O. Killijian. Meeting points in ridesharing: A privacy-preserving preserving approach. *Transportation Research*, 72:239–253, 2016.

[4] M. Arenas, V. Kantere, A. Kementsietsidis, I. Kiringa, R. C. Summers, and C. Wood. The essence of EU Competition Law, the Consumer Interest and Data. *2014.*

[5] Y.-A. de Montjoye, E. Shmueli, S. S. Wang, and A. S. Pentland. OpenPDS: Protecting the privacy of metadata through SafeAnswers. *PLOS ONE*, 4(12):1371–1374, 2011.

[6] Z. Hu, H. Pacheco, and S. Fischer. Validity checking of relational views. *ACM Transactions on Database Systems*, 6(4):557–575, 1981.

[7] D. M. J. Barbosa, J. Cretin, J. N. Foster, M. Greenberg, and B. C. Pierce. Matching lenses: Alignment and view update. In *ICFP*, pages 193–204, 2010.

[8] A. Bohannon, J. N. Foster, B. C. Pierce, A. Pilkiewicz, and A. Schmitt. Boomerang: Resourceful lenses for string data. In *POPL*, pages 407–419, 2008.

[9] A. Bohannon, B. C. Pierce, and J. A. Vaughan. Relational lenses: A language for updatable views. In *PODS*, pages 338–347, 2006.

[10] A. Bohannon, J. A. Vaughan, and B. C. Pierce. Relational lenses: A language for updatable views. Technical Report MS-CIS-05-27, 2005.

[11] E. F. Codd. Recent investigations in a relational database system. *Information Processing*, 74:1017–1021, 1974.

[12] K. Czarnecki, J. N. Foster, Z. Hu, R. Lämmel, A. Schirr, and J. Terverliger. Bidirectional transformations: A cross-discipline perspective. In *ICMT*, pages 260–283, 2009.

[13] D. M. J. Barbosa, J. Cretin, J. N. Foster, M. Greenberg, and B. C. Pierce. Matching lenses: Alignment and view update. In *ICFP*, pages 193–204, 2010.

[14] Y.-A. de Montjoye, E. Shmueli, S. S. Wang, and A. S. Pentland. OpenPDS: Protecting the privacy of metadata through SafeAnswers. *PLOS ONE*, 9(7), 2014.

[15] A. Doan, A. Y. Halevy, and Z. G. Ives. Principles of Data Integration. Morgan Kaufmann, 2012.

[16] E. B. Fernandez, R. C. Summers, and C. Wood. *Database Security and Integrity*. Addison-Wesley Longman Publishing Co., Inc., 1981.

[17] F. Ferretti. *EU Competition Law, the Consumer Interest and Data*. 2014.

[18] S. Fischer, Z. Hu, and H. Pacheco. The essence of bidirectional programming. *SCIENCE CHINA Information Sciences*, 58(5):1–21, 2015.

[19] J. N. Foster, M. B. Greenwald, J. T. Moore, B. C. Pierce, and A. Schmitt. Combinators for bidirectional tree transformations: A linguistic approach to the view-update problem. *ACM Transactions on Programming Languages and Systems*, 29(3):17, 2007.

[20] J. N. Foster, B. C. Pierce, and S. Zdancewic. Updatable security views. In *CSF*, pages 60–74, 2009.

[21] M. Furuhata, M. Dessouky, F. Ordóñez, M.-E. Brunet, X. Wang, and S. Koenig. Ridesharing: The state-of-the-art and future directions. *Transportation Research Part B: Methodological*, 57:28–46, 2013.

[22] A. Ghosh and A. Roth. Selling privacy at auction. *Games and Economic Behavior*, 91:334–346, 2015.

[23] B. Golshan, A. Halevy, G. Mihaila, and W.-C. Tan. Data integration: After the teenage years. In *PODS*, pages 101–106, 2017.

[24] A. Y. Halevy, Z. G. Ives, J. Madhavan, P. Mork, D. Suciu, and I. Tatarinov. The Piazza peer data management system. *IEEE Transactions on Knowledge and Data Engineering*, 16(7):787–798, 2004.

[25] A. Y. Halevy, Z. G. Ives, P. Mork, and I. Tatarinov. Piazza: Data management infrastructure for Semantic Web applications. In *WWW*, pages 556–567, 2003.

[26] S. J. Hegner. An order-based theory of updates for closed database views. *Annals of Mathematics and Artificial Intelligence*, 40:63–125, 2004.

[27] S. Hidaka, Z. Hu, K. Inaba, H. Kato, K. Matsuda, and K. Nakano. Bidirectionalizing graph transformations. In *ICFP*, pages 205–216, 2010.

[28] M. Hofmann, B. C. Pierce, and D. Wagner. Symmetric lenses. In *POPL*, pages 371–384, 2011.

[29] R. Horn. Language integrated incremental relational lenses. Master’s thesis, School of Informatics, University of Edinburgh, 2017.

[30] R. Horn and J. Cheney. Incremental relational lenses. In *First Workshop on Incremental Computing, 2017*. PLDI workshop [https://pldi17.sigplan.org/track/ic-2017-papers](https://pldi17.sigplan.org/track/ic-2017-papers).

[31] Z. Hu, H. Pacheco, and S. Fischer. Validity checking of putback transformations in bidirectional programming. In *FM*, pages 1–15, 2014.

[32] Z. Ives, N. Khanselwal, A. Kapur, and M. Cahir. ORCHESTRA: Rapid, collaborative sharing of dynamic data. In *CIDR*, pages 107–118, 2005.

[33] V. Kantere, D. Bousounis, and T. Sellis. GrouPeer: A system for clustering P2P. *PVLDB*, 4(12):1371–1374, 2011.

[34] V. Kantere, D. Tsoumakos, T. Sellis, and N. Roussopoulos. GrouPeer: Dynamic clustering of P2P databases. *Information Systems*, 34(1):62–86, 2009.

[35] Y. Kanza and H. Samet. An online marketplace for geosocial data. In *SIGSPATIAL*, pages 10.1–10.14, 2015.

[36] G. Karvounarakis, T. J. Green, Z. G. Ives, and V. I. Tannen. Collaborative data sharing via update exchange and provenance. *ACM Transactions on Database Systems*, 38(3):19:1–19:42, 2013.

[37] A. Kawasaki, A. Yamamoto, P. Koudela, R. Acierio, T. Nemoto, M. Kitsuregawa, and T. Koike. Data integration and analysis system (DIAS) contributing to climate change analysis and disaster risk reduction. *Data Science Journal*, 16(41):1–17, 2017.

[38] A. Keller. Choosing a view update translator by dialog at view definition time. In *VLDB*, pages 467–474, 1986.

[39] A. Kementsietsidis, M. Arenas, and R. J. Miller. Mapping data in peer-to-peer systems: Semantics and algorithmic issues. In *SIGMOD*, pages 325–336, 2003.
[40] H.-S. Ko and Z. Hu. An axiomatic basis for bidirectional programming. *POPL*, 2(41):41:1–41:29, 2018.

[41] H.-S. Ko, T. Zan, and Z. Hu. BiGUL: A formally verified core language for putback-based bidirectional programming. In *Workshop on Partial Evaluation and Program Manipulation*, pages 61–72, 2016.

[42] J. A. Larson and A. P. Sheth. Updating relational views using knowledge at view definition and view update time. *Information Systems*, 16(2):145 – 168, 1991.

[43] C. Li, D. Y. Li, G. Miklau, and D. Suciu. A theory of pricing private data. *ACM Transaction of Database System*, 39(4):34:1–34:28, 2014.

[44] C. Li, D. Y. Li, G. Miklau, and D. Suciu. A theory of pricing private data. *Communication of ACM*, 60(12):79–86, 2017.

[45] X. Li, J. Yao, X. Liu, and H. Guan. A first look at information entropy-based data pricing. In *ICDCS*, pages 2053–2060, 2017.

[46] Y. Masunaga. A relational database view update translation mechanism. In *VLDB*, pages 309–320, 1984.

[47] Y. Masunaga. An intention-based approach to the updatability of views in relational databases. In *IMCOM*, pages 13:1–13:8, 2017.

[48] Y. Masunaga. Extending the view updatability of relational databases from set semantics to bag semantics and its implementation on PostgreSQL. In *IMCOM*, 2018.

[49] K. Matsuda, Z. Hu, K. Nakano, M. Hamana, and M. Takeichi. Bidirectionalization transformation based on automatic derivation of view complement functions. In *ICFP*, pages 47–58, 2007.

[50] A. Muschalle, F. Stahl, A. Löser, and G. Vossen. Pricing approaches for data markets. In *Enabling Real-Time Business Intelligence*, pages 129–144, 2012.

[51] S. Nativi, M. Craglia, and J. Pearlman. Earth science infrastructures interoperability: The brokering approach. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 6(3):1118–1129, 2013.

[52] OECD. Exploring the economics of personal data. Technical report, 2013.

[53] H. Pacheco, Z. Hu, and S. Fischer. Monadic combinators for “putback” style bidirectional programming. In *Workshop on Partial Evaluation and Program Manipulation*, pages 39–50, 2014.

[54] H. Pacheco, T. Zan, and Z. Hu. BiFuX: a bidirectional functional update language for XML. In *PPDP*, pages 147–158, 2014.

[55] B. C. Pierce and A. Schmitt. Lenses and view update translation. Working Draft, University of Pennsylvania, 2003.

[56] A. Roth. Buying private data at auction: The sensitive surveyor’s problem. *ACM SIGecom Exchanges*, 11(1):1–8, 2012.

[57] A. Roth. Technical perspective: Pricing information (and its implications). *Communication of the ACM*, 60(12):78–78, 2017.

[58] A. Silberstein, J. Terrace, B. F. Cooper, and R. Ramakrishnan. Feeding Frenzy: Selectively materializing users’ event feeds. In *SIGMOD*, 2010.

[59] J. Terwilliger, A. Cleve, and C. Curino. How clean is your sandbox? In *ICMT*, pages 1–23, 2012.

[60] W. Tong, J. Hua, and S. Zhong. A jointly differentially private scheduling protocol for ridesharing services. *IEEE Transactions on Information Forensics and Security*, 12(10), 2017.

[61] J. Voigtländer. Bidirectionalization for free! In *POPL*, pages 165–176, 2009.

[62] Y. Xiong, D. Liu, Z. Hu, H. Zhao, M. Takeichi, and H. Mei. Towards automatic model synchronization from model transformations. In *ASE*, pages 164–173, 2007.

[63] T. Zan, L. Liu, H. Ko, and Z. Hu. Brul: A putback-based bidirectional transformation library for updatable views. In *ETAPS*, pages 77–89, 2016.

[64] J. Zhou, P.-A. Larson, and J. Goldstein. Dynamic materialized views. In *ICDE*, 2007.