Determining the currency of data

Citation for published version:

Digital Object Identifier (DOI):
10.1145/1989284.1989295

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Early version, also known as pre-print

Published In:
PODS '11 Proceedings of the thirtieth ACM SIGMOD-SIGACT-SIGART symposium on Principles of database systems

General rights
Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.
Determining the Currency of Data

Wenfei Fan
University of Edinburgh & Harbin Institute of Technology
wenfei@inf.ed.ac.uk

Floris Geerts
School of Informatics
University of Edinburgh
fgeerts@inf.ed.ac.uk

Jef Wijsen
Institut d’Informatique
Université de Mons
jef.wijsen@umons.ac.be

Abstract

Data in real-life databases become obsolete rapidly. One often finds that multiple values of the same entity reside in a database. While all of these values were once correct, most of them may have become stale and inaccurate. Worse still, the values often do not carry reliable timestamps. With this comes the need for studying data currency, to identify the current value of an entity in a database and to answer queries with the current values, in the absence of timestamps.

This paper investigates the currency of data. (1) We propose a model that specifies partial currency orders in terms of simple constraints. The model also allows us to express what values are copied from other data sources, bearing currency orders in those sources, in terms of copy functions defined on correlated attributes. (2) We study fundamental problems for data currency, to determine whether a specification is consistent, whether a value is more current than another, and whether a query answer is certain no matter how partial currency orders are completed. (3) Moreover, we identify several problems associated with copy functions, to decide whether a copy function imports sufficient current data to answer a query, whether such a function copies redundant data, whether a copy function can be extended to import necessary current data for a query while respecting the constraints, and whether it suffices to copy data of a bounded size. (4) We establish upper and lower bounds of data complexity, and for a variety of query languages. We also identify special cases that warrant lower complexity.

Categories and Subject Descriptors: H.2.3 [Information Systems]: Database Management — Languages; F.4.1 [Mathematical Logic and Formal Languages]: Mathematical Logic — Computational Logic

General Terms: Languages, Theory, Design.

1. Introduction

The quality of data in a real-life database quickly degenerates over time. Indeed, it is estimated that “2% of records in a customer file become obsolete in one month” [15]. That is, in a database of 500,000 customer records, 10,000 records may go stale per month, 120,000 records per year, and within two years about 50% of all the records may be obsolete. In light of this, we often find that multiple values of the same entity reside in a database, which were once correct, i.e., they were true values of the entity at some time. However, most of them have become obsolete and inaccurate. As an example from daily life, when one moves to a new address, her bank may retain her old address, and worse still, her credit card bills may still be sent to her old address for quite some time (see, e.g., [22] for more examples). Stale data is one of the central problems to data quality. It is known that dirty data costs US businesses 600 billion USD each year [15], and stale data accounts for a large part of the losses.

This highlights the need for studying the currency of data, which aims to identify the current values of entities in a database, and to answer queries with the current values.

The question of data currency would be trivial if all data values carried valid timestamps. In practice, however, one often finds that timestamps are unavailable or imprecise [34]. Add to this the complication that data values are often copied or imported from other sources [2, 12, 13], which may not support a uniform scheme of timestamps. These make it challenging to identify the current values.

Not all is lost. One can often deduce currency orders from the semantics of the data. Moreover, data copied from other sources inherit currency orders from those sources. Taken together, these often provide sufficient current values of the data to answer certain queries, as illustrated below.

Example 1.1: Consider two relations of a company shown in Fig. 1. Each Emp tuple is an employee record with name, address, salary and marital status. A Dept tuple specifies the name, manager and budget of a department. Records in these relations may be stale, and do not carry timestamps. By entity identification techniques (see, e.g., [16]), we know
that tuples $s_1$, $s_2$ and $s_3$ refer to the same employee Mary, but $s_4$ and $s_5$ represent different people distinct from Mary. Consider the following queries posed on these relations.

1. Query $Q_1$ is to find Mary’s current salary. No timestamps are available for us to tell which of 50k or 80k is more current. However, we may know that the salary of each employee in the company does not decrease, as commonly found in real world. This yields currency orders $s_1 \prec_{\text{Salary}} s_3$ and $s_2 \prec_{\text{Salary}} s_3$, i.e., $s_3[\text{Salary}]$ is more current than both $s_1[\text{Salary}]$ and $s_2[\text{Salary}]$. Hence the answer to $Q_1$ is 80k.

2. Query $Q_2$ is to find Mary’s current last name. We can no longer answer $Q_2$ as above. Nonetheless, we may know the following: (a) marital status can only change from single to married and from married to divorced; but not from married to single; and (b) $\text{Emp}$ tuples with the most current marital status also contain the most current last name. Therefore, $s_1 \prec_{\text{LN}} s_2$ and $s_1 \prec_{\text{LN}} s_3$, and the answer to $Q_2$ is Dupont.

3. Query $Q_3$ is to find Mary’s current address. We may know that $\text{Emp}$ tuples with the most current status or salary contain the most current address. Putting this and (1) above together, we know that the answer to $Q_3$ is “6 Main St”.

4. Finally, query $Q_4$ is to find the current budget of department R&D. Again no timestamps are available for us to evaluate the query. However, we may know the following: (a) $\text{Dept}$ tuples $t_1$ and $t_2$ have copied their $\text{mgrAddr}$ values from $s_1[\text{address}]$ in $\text{Emp}$; similarly, $t_3$ has copied from $s_3$, and $t_4$ from $s_4$; and (b) in $\text{Dept}$, tuples with the most current address also have the most current budget. Taken together, these tell us that $t_1 \prec_{\text{Budget}} t_3$ and $t_2 \prec_{\text{Budget}} t_4$. Observe that we do not know which budget in $t_3$ or $t_4$ is more current. Nevertheless, in either case the most current budget is 6000k, and hence it is the answer to $Q_4$.

These suggest that we give a full treatment of data currency, and answer the following questions. How should we specify currency orders on data values in the absence of timestamps but in the presence of copy relationships? When currency orders are only partly available, can we decide whether an attribute value is more up-to-date than another? How can we answer a query with only current data?

A model for data currency. To answer these questions, we approach data currency based on the following.

1. For each attribute $A$ of a relation $D$, we assume an (implicit) currency order $\prec_A$ on its tuples such that for tuples $t_1$ and $t_2$ in $D$ that represent the same real-world entity, $t_1 \prec_A t_2$ indicates that $t_2$ is more up-to-date than $t_1$ in the $A$ attribute value. Here $\prec_A$ is not a total order since in practice, currency information is only partially available. Note that for distinct attributes $A$ and $B$, we may have $t_1 \prec_A t_2$ and $t_2 \prec_B t_1$, i.e., there may be no single tuple that is most up-to-date in all attribute values.

2. We express additional currency relationships as denial constraints [3, 7], which are simple universally quantified FO sentences that have been used to improve the consistency of data. We show that the same class of constraints also suffices to express currency semantics commonly found in practice. For instance, all the currency relations we have seen in Example 1.1 can be expressed as denial constraints.

3. We define a copy relationship from relation $D_i$ to $D_k$ in terms of a partial mapping, referred to as a copy function. It specifies what attribute values in $D_i$ have been copied from $D_k$ along with their currency orders in $D_i$. It also assures that correlated attributes are copied together. As observed in [2, 12, 13], copy functions are common in real world, and can be automatically discovered.

Putting these together, we consider $\mathbf{D} = (D_1, \ldots, D_n)$, a collection of relations such that (a) each $D_i$ has currency orders partially defined on its tuples for each attribute, indicating available currency information; (b) each $D_i$ satisfies a set $\Sigma_i$ of denial constraints, which expresses currency orders derived from the semantics of the data; and (c) for each pair $D_j, D_k$ of relations, there are possibly copy functions defined on them, which import values from one to another.

We study consistent completions $D'_i$ of $D_j$, which extend $\prec_A$ in $D_j$ to a total order on all tuples pertaining to the same entity, such that $D'_j$ satisfies $\Sigma_j$ and constraints imposed by the copy functions. One can construct from $D'_j$ the current tuple for each entity w.r.t. $\prec_A$, which contains the entity’s most current $A$ value for each attribute $A$. This yields the current instance of $D'_j$ consisting of only the current tuples of the entities in $D_j$, from which currency orders are removed. We evaluate a query $Q$ on current instances of relations in $\mathbf{D}$, without worrying about currency orders. We study certain current answers to $Q$ in $\mathbf{D}$, i.e., tuples that are the answers to $Q$ in all consistent completions of $\mathbf{D}$.

Reasoning about data currency. We study fundamental problems for data currency. (a) The consistency problem is to determine, given denial constraints $\Sigma_j$ imposed on each $D_j$ and copy functions between these relations, whether there exist consistent completions of every $D_j$, i.e., whether the specification makes sense. (b) The certain ordering problem is to decide whether a currency order is contained in all consistent completions. (c) The deterministic current instance problem is to determine whether the current instance of each relation remains unchanged for all consistent completions. The ability to answer these questions allows us to determine whether an attribute value is certainly more current than another, and to identify the current value of an entity. (d) The certain current query answering problem is to decide whether a tuple $t$ is a certain current answer to a query $Q$, i.e., it is certainly computed using current data.

Currency preserving copy functions. It is natural to ask what values should be copied from one data source to another in order to answer a query. To characterize this intuition we introduce a notion of currency preservation. Consider data sources $\mathbf{D} = (D_1, \ldots, D_n)$ and $\mathbf{D}' = (D'_1, \ldots, D'_n)$, each consisting of a collection of relations with denial constraints imposed on them. Consider copy functions $\mathbf{p}$ from relations in $\mathbf{D}'$ to those in $\mathbf{D}$. For a query $Q$ posed on $\mathbf{D}$, we say that $\mathbf{p}$ is currency preserving if no matter how we extend $\mathbf{p}$ by copying from $\mathbf{D}'$ more values of those entities in $\mathbf{D}$, the certain current answers to $Q$ in $\mathbf{D}$ remain unchanged. In other words, $\mathbf{p}$ has already imported data values needed for computing certain current answers to $Q$.

We identify several problems associated with currency-preserving copy functions. (a) The currency preservation problem is to determine, given $\mathbf{Q}, \mathbf{p}, \mathbf{D}, \mathbf{D}'$ and their denial
related work. There has been a host of work on temporal databases (see, e.g., [8, 30] for surveys). Temporal databases provide support for valid time, transaction time, or both. They assume the availability of timestamps, and refer to “now” by means of current-time variables [9, 14]. Dynamic and temporal integrity constraints allow to restrict the set of legal database evolutions. Our currency model differs from temporal data models in several respects. We do not assume explicit timestamps. Nevertheless, if such timestamps are present, they can be related to currency by means of denial constraints. Unlike temporal databases that timestamp entire tuples, our model allows that different values within the same tuple have distinct currencies. That is, the same tuple can contain an up-to-date value for one attribute, and an outdated value for another attribute.

Since currency orders are different from temporal orders used in temporal databases, our currency (denial) constraints differ from traditional temporal constraints. Currency constraints can sometimes be derived from temporal constraints. For example, when salaries are constrained to be non-decreasing, we can express that the highest salary is the most current one. Also, our copy functions can require certain attributes to be copied together when these attributes cannot change independently, as for example expressed by the dynamic functional dependencies in [33].

Closer to this work are [31, 24, 25, 20] on querying indefinite data. In [31], the evaluation of CQ queries is studied on data that is linearly ordered but only provides a partial order. The problem studied there is similar to (yet different from) certain current query answering. An extension of conditional tables [19, 21] is proposed in [24] to incorporate indefinite temporal information, and in that setting, the complexity bounds for FO query evaluation are provided in [25]. Recently the non-emptiness problem for datalog on linear orders is investigated in [20]. However, none of these considers copying data from external sources, or the analyses of certain ordering and currency-preserving copy functions. In addition, we answer queries using current instances of relations, which are normal relations without (currency) ordering. This semantics is quite different from its counterparts in previous work. We also consider denial constraints and copy functions, which are not expressible in CQ or datalog studied in [31, 20]. In contrast to our work, [24, 25] assume explicit timestamps, while we use denial constraints to specify data currency. To encode denial constraints in extended conditional tables of [24, 25], an exponential blowup is inevitable. Because of these reasons, the results of [31, 24, 25, 20] cannot carry over to our setting, and vice versa.

There has also been a large body of work on the temporal constraint satisfaction problem (TCSP), which is to find a valuation of temporal variables that satisfies a set of temporal constraints (see, e.g., [4, 29]). It differs from our consistency problem in that it considers neither completions of currency orders that satisfy denial constraints, nor copy relationships. Hence the results for TCSP are not directly applicable to our consistency problem, and vice versa.

Copy relationships between data sources have recently been studied in [2, 12, 13]. The previous work has focused on automatic discovery of copying dependencies and functions. Copy relationships are also related to data provenance, which studies propagation of annotations in data transformations and updates (see [5, 6] for recent surveys on data provenance). However, to the best of our knowledge, no previous work has studied currency-preserving copy functions and their associated problems.

Denial constraints have proved useful in detecting data inconsistencies and data repairing (see, e.g., [3, 7]). We adopt the same class of constraints to specify the currency of data, so that data currency and consistency could be treated in a uniform logical framework. Denial constraints can also be automatically discovered, along the same lines as data dependency profiling (see, e.g., [17]).

The study of data currency is also related to research on incomplete information (see [32] for a survey), when missing data concerns data currency. In contrast to that line of work, we investigate how to decide whether a value is more current than another, and study the properties of copy functions. We use denial constraints to specify data currency, which are, as remarked earlier, more succinct than, e.g., C-tables and V-tables for representing incomplete information [19, 21]. In addition, we evaluate queries using current instances, a departure from the study of incomplete information.

Certain query answers have been studied in data integration and exchange. In data integration, for a query Q posed on a global database D_G, it is to find the certain answers to Q over all data sources that are consistent with D_G w.r.t. view definitions (see e.g., [27]). In data exchange, it is to find the certain answers to a query over all target
databases generated from data sources via schema mapping (see [23]). In contrast, we consider certain answers to a query over all completions of currency orders, which satisfy denial constraints and constraints from copy functions. Certain current query answering is also different from consistent query answering (see, e.g., [3, 7]), which is to find certain answers to a query over all repairs of a database and does not distinguish between stale and current data in the repairs. Finally, whereas it may be possible to model our setting as a data exchange scenario with built-in constraints [11], our complexity results do not follow gratuitously and a careful analysis of the chase is required in this setting.

**Organization.** Section 2 presents the data currency model. Section 3 states its related problems. Section 4 establishes the complexity bounds of those problems. Section 5 introduces the notion of currency preservation and its fundamental problems, followed by their complexity analysis in Section 6. Section 7 summarizes the main results of the paper.

## 2. Data Currency

We introduce a model for specifying data currency. A specification consists of (a) partial currency orders, (b) denial constraints, and (c) copy functions. We first present these notions, and then study consistent completions of currency orders. Finally, we show how queries are answered on current instances that are derived from these completions.

### Data with partial currency orders

A relation schema is specified as $R = (\text{Emp}, A_1, \ldots, A_n)$, where $\text{Emp}$ denotes entity id that identifies tuples pertaining to the same entity, as introduced by Codd [10]. EID values can be obtained using entity identification techniques (a.k.a. record linkage, matching and data deduplication; see, e.g., [16]). A finite instance $D$ of $R$ is referred to as a normal instance of $R$.

A temporal instance $D_t$ of $R$ is given as $(D, \prec_{A_1}, \ldots, \prec_{A_n})$, where each $\prec_{A_i}$ is a strict partial order on $D$ such that for tuples $t_1$ and $t_2$ in $D$, $t_1 \prec_{A_i} t_2$ implies $t_1[e\text{EID}] = t_2[e\text{EID}]$. We call $\prec_{A_i}$ the currency order for attribute $A_i$. Recall that a strict partial order is irreflexive and transitive, and therefore asymmetric. Intuitively, if $t_1 \prec_{A_i} t_2$, then $t_1$ and $t_2$ refer to the same entity, and $t_2$ contains a more current $A_i$-value for that entity than $t_1$, i.e., $t_2$ is more current than $t_1$ in attribute $A_i$. A currency order $\prec_{A_i}$ is empty when no currency information is known for attribute $A_i$. A completion of $D_t$ is a temporal instance $D_{t+} = (D, \prec_{A_1}, \ldots, \prec_{A_n})$ of $R$, such that for each $i \in [1, n]$, (1) $\prec_{A_i} \subseteq \prec_{A_i}$, and (2) for all $t_1, t_2 \in D$, $t_1$ and $t_2$ are comparable under $\prec_{A_i}$ iff $t_1[e\text{EID}] = t_2[e\text{EID}]$. The latter condition implies that $\prec_{A_i}$ induces a total order on tuples that refer to the same entity, while tuples representing distinct entities are not comparable under $\prec_{A_i}$. We call $\prec_{A_i}$ a completed currency order.

### Denial constraints

We use denial constraints [3, 7] to specify additional currency information derived from the semantics of data, which enriches $\prec_{A_i}$. A denial constraint $\varphi$ for $R$ is a universally quantified FO sentence of the form:

$$\forall t_1, \ldots, t_k : R \left( \bigwedge_{j \in [1, k]} (t_j[e\text{EID}] = t_j[e\text{EID}] \land \psi) \rightarrow t_u \prec_{A_i} t_e, \right)$$

where $u, v \in [1, k]$, each $t_j$ is a tuple variable denoting a tuple of $R$, and $\psi$ is a conjunction of predicates and does not (1) $t_j \prec_{A_i} t_e$, i.e., $t_e$ is more current than $t_j$ in attribute $A_i$; (2) $t_j[A_i] = t_k[A_i]$ (resp. $t_j[A_i] \neq t_k[A_i]$), i.e., $t_j[A_i]$ and $t_k[A_i]$ are identical (resp. distinct) values; (3) $t_j[A_i] = c$ (resp. $t_j[A_i] \neq c$), where $c$ is a constant; and (4) possibly other built-in predicates defined on particular domains.

### Example 2.1

Recall relations $\text{Emp}$ and $\text{Dept}$ given in Fig. 1. Denial constraints on these relations include:

- $\varphi_1$: $\forall s, t: \text{Emp}(s[e\text{EID}] = t[e\text{EID}] \land \psi) \rightarrow t \prec_{\text{salary}} s$
- $\varphi_2$: $\forall s, t: \text{Emp}(s[e\text{EID}] = t[e\text{EID}] \land s[\text{status}] = \text{"married" } \land t[\text{status}] = \text{"single"}) \rightarrow t \prec_{\text{fnos}} s$
- $\varphi_3$: $\forall s, t: \text{Emp}(s[e\text{EID}] = t[e\text{EID}] \land s[\text{salary}] = \text{\$15000}) \rightarrow t \prec_{\text{address}} s$
- $\varphi_4$: $\forall s, t: \text{Dept}(s[e\text{EID}] = t[e\text{EID}] \land t[\text{mgrAddr}] = \text{\$20000}) \rightarrow t \prec_{\text{budget}} s$

Here $\varphi_1$ states that when $\text{Emp}$ tuples $s$ and $t$ refer to the same employee, if $s[\text{salary}] > t[\text{salary}]$, then $s$ is more current than $t$ in attribute salary. Note that $\prec$ denotes the built-in predicate "less-than" in the numeric domain of salary, whereas $\prec$ is the currency order for salary. Constraint $\varphi_2$ asserts that if $s[\text{status}]$ is married and $t[\text{status}]$ is single, then $s$ is more current than $t$ in LN. Constraint $\varphi_3$ states that if $s$ is more current than $t$ in salary, then $s$ is also more current than $t$ in address; similarly for $\varphi_4$.

### Copy functions

Consider two temporal instances $D_t(1) = (D_1, \prec_{A_1}, \ldots, \prec_{A_n})$ and $D_t(2) = (D_2, \prec_{B_1}, \ldots, \prec_{B_n})$ of (possibly distinct) relation schemas $R_1$ and $R_2$, respectively. A copy function $\phi$ of signature $R_1[A] \leftarrow R_2[B]$ is a partial mapping from $D_1$ to $D_2$, where $A = (A_1, \ldots, A_n)$ and $B = (B_1, \ldots, B_n)$, denoting attributes in $R_1$ and $R_2$, respectively. Here $\phi$ is required to satisfy the copying condition: for each tuple $t \in D_1$, if $\rho(t) = s$, then $\phi(A) = \phi(B)$ for all $i \in [1, l]$. Intuitively, for tuples $t \in D_1$ and $s \in D_2$, $\rho(t) = s$ indicates that the values of the $A$ attributes of $t$ have been imported from the $B$ attributes of tuple $s$ in $D_2$. Here $A$ specifies a list of correlated attributes that should be copied together.

The copy function $\phi$ is called $\prec$-compatible (w.r.t. the currency orders found in $D_t(1)$ and $D_t(2)$) if for all $t_1, t_2 \in D_1$, for each $i \in [1, l]$, if $\rho(t_1) = s_1$, $\rho(t_2) = s_2$, then $t_1[e\text{EID}] = t_2[e\text{EID}]$ and $s_1[e\text{EID}] = s_2[e\text{EID}]$, then $s_1 \prec_{A_i} s_2$ implies $t_1 \prec_{A_i} t_2$.

Intuitively, $\prec$-compatibility requires that copy functions preserve currency orders. In other words, when attribute values are imported from $D_2$ to $D_1$, the currency orders on corresponding tuples defined in $D_t(1, 2)$ are inherited by $D_t(1, 2)$.

### Example 2.2

Consider relations $\text{Emp}$ and $\text{Dept}$ shown in Fig. 1. A copy function $\rho$ of signature $\text{Dept}[\text{mgrAddr}] \leftarrow \text{Emp}[\text{address}]$, depicted in Fig. 1 by arrows, is given as follows: $\rho(t_1) = s_1$, $\rho(t_2) = s_1$, $\rho(t_3) = s_3$ and $\rho(t_4) = s_4$. That is, the $\text{mgrAddr}$ values of $t_1$ and $t_2$ have both been imported from $s_1[\text{address}]$, while $t_3[\text{mgrAddr}]$ and $t_4[\text{mgrAddr}]$ are copied from $s_3[\text{address}]$ and $s_4[\text{address}]$, respectively. The function satisfies the copying condition, since $t_1[\text{mgrAddr}] = t_2[\text{mgrAddr}] = s_1[\text{address}]$ and $t_3[\text{mgrAddr}] = s_3[\text{address}]$ and $t_4[\text{mgrAddr}] = s_4[\text{address}]$.

The EID value, if these tuples satisfy the predicates in follow.

Suppose that $\prec$ is empty for each attribute $A$ in Emp or Dept. Then copy function $\rho$ is $\prec$-compatible w.r.t. these temporal instances of Emp and Dept. In contrast, as-
sume that partial currency orders $s_1 \prec \text{address} s_3$ on Emp and $t_3 \prec \text{mgrAdd} t_1$ are given. Then $\rho$ is not $\prec$-compatible. Indeed, since $s_1$, $s_3$ pertain to the same person Mary, and $t_1$, $t_3$ to the same department R&D, the relation $s_1 \prec \text{address} s_3$ should carry over into $t_1 \prec \text{mgrAdd} t_3$, as $\rho(t_1) = s_1$ and $\rho(t_3) = s_3$. Clearly, $t_3 \prec \text{mgrAdd} t_1$ and $t_1 \prec \text{mgrAdd} t_3$ are contradictory.

**Consistent completions of temporal orders.** A specification $S$ of currency data consists of (1) a collection of temporal instances $D_{(i,j)}$ of schema $R_i$ for $i \in [1, l]$, (2) the set $\Sigma_i$ of denial constraints imposed on each $D_{(i,j)}$, and (3) a (possibly empty) copy function $\rho_{(i,j)}$ that imports data from $D_{(i,j)}$ to $D'_{(i,j)}$ for $i,j \in [1, l]$. It specifies data values and entities (by normal instances embedded in $D_{(i,j)}$), partial currency orders known for each relation (by $D_{(i,j)}$), additional currency information derived from the semantics of the data $(\Sigma_i)$, and data that has been copied from one source to another ($\rho_{(i,j)}$). These $D_{(i,j)}$'s may denote different data sources, i.e., they may not necessarily be in the same database.

A consistent completion $D'$ of $S$ consists of temporal instances $D'_{(i,j)}$ of $R_i$ such that for all $i,j \in [1, l]$,

1. $D'_{(i,j)}$ is a completion of $D_{(i,j)}$.
2. $D'_{(i,j)} = \Sigma_i$, and
3. $\rho_{(i,j)}$ is compatible w.r.t. the completed currency orders found in $D'_{(i,j)}$ and $D_{(i,j)}$.

We use $\text{Mod}(S)$ to denote the set of all consistent completions of $S$. We say that $S$ is consistent if $\text{Mod}(S) \neq \emptyset$, i.e., there exists at least one consistent completion of $S$.

Intuitively, if $D_{(i,j)}(e) = (D_i, \prec A_1, \ldots, \prec A_n)$ is part of a specification and $D'_{(i,j)}(e) = (D_i, \prec A_1', \ldots, \prec A_n')$ is part of a consistent completion of that specification, then each $\prec A_i'$ extends $\prec A_i$ to a completed currency order, and the completed orders satisfy the denial constraints $\Sigma_i$ and the constraints imposed by copy functions. Observe that the copying condition and $\prec$-compatibility impose constraints on consistent completions. This is particularly evident when a data source imports data from multiple sources, and when two data sources copy from each other, directly or indirectly. In addition, these constraints interact with denial constraints.

**Example 2.3:** Consider a specification $S_0$ consisting of Emp and Dept of Fig. 1, the denial constraints $\varphi_2 \prec \varphi_4$ given in Example 2.1, and the copy $\rho$ defined in Example 2.2. Assume that no currency orders are given for Emp and Dept initially. A consistent completion $D_0'$ of $S_0$ defines (1) $s_1 \prec A_2$ when $A$ ranges over FN, LN, address, salary and status for Emp tuples, and (2) $t_1 \prec B_2$ when $B$ ranges over mgrFN, mgrLN, mgrAddr and budget for Dept tuples (here we assume that $\text{name}$ is the EID attribute of Dept). One can verify that $D_0'$ satisfies the denial constraints and the constraints imposed by $\rho$, and hence, $D_0' \in \text{Mod}(S_0)$. Note that no currency order is defined between any of $s_1$, $s_2$, $s_3$ and any of $s_4$, $s_5$, since they represent different entities. Suppose that Dept also copies from a source $D_1$ consisting of a single tuple $s_1'$, which is the same as $s_1$ except that $s_1'[\text{address}] = "5 Elm Ave"$. It uses a copy function $\rho_1$ that imports $s_1'[\text{address}]$ to $t_1[\text{mgrAddr}]$. Then there exists no consistent completion in this setting since $t_1$ may not import distinct values $s_1'[\text{address}]$ and $s_1[\text{address}]$ for $t_1[\text{mgrAddr}]$. In other words, the constraints imposed by the copying conditions of $\rho$ and $\rho_1$ cannot be satisfied at the same time.

| $D_1$ | a normal instance of a relation schema $R$ |
| $D_r$ | a temporal instance of $R$ with partial currency orders |
| $D'_{\rho}$ | a completion of partial currency orders in $D_r$ |
| $S$ | a specification of data currency |
| $D^*$ | a consistent completion of a specification $S$ |
| $\text{LST}(D^*)$ | the current instance of $D^*$ |
| $\rho$ | a collection of copy functions in $S$ |
| $\rho'$ | an extension of copy functions in $S$ |
| $S^*$ | an extension of specification $S$ by $\rho'$ |

**Table 1: A summary of notations**

As another example, suppose that there is a copy function $\rho_2$ that imports budget attribute values of $t_1$ and $t_3$ from the budget attributes of $s_1'$ and $s_2'$ in another source $D_2$, respectively, where $s_1' = t_1$ and $s_2' = t_3$, but in $D_2$, $s_3' \prec \text{budget} s_1'$. Then there is no consistent completion in this setting either. Indeed, all completed currency orders of $\prec$-budget in Dept have to satisfy denial constraints $\varphi_2$, $\varphi_3$, and $\varphi_4$, which enforce $t_1 \prec \text{budget} t_3$, but $\rho_2$ is not $\prec$-compatible with this currency order. This shows the interaction between denial constraints and currency constraints of copy functions.

**Current instances.** In a temporal instance $D_i = (D_i, \prec A_1, \ldots, \prec A_n)$ of $R_i$, let $E = \{t[EID] \mid t \in D_i\}$, and for each entity $e \in E$, let $I_e = \{t \in D_i \mid \text{EID}=e\}$. That is, $E$ contains all EID values in $D_i$, and $I_e$ is the set of tuples pertaining to the entity whose EID is $e$.

In a completion $D_i'$ of $D_i$, for each attribute $A$ of $R_i$, the current $A$ value for entity $e \in E$ is the value $t[A]$, where $t$ is the greatest (i.e., most current) tuple in the totally ordered set $(I_e, \prec A)$. The current tuple for entity $e \in E$, denoted by $\text{LST}(e, D_i')$, is the tuple $t_e$ such that for each attribute $A$ of $R_i$, $t_e[A]$ is the current $A$ value for entity $e$.

We use $\text{LST}(D_i')$ to denote $\{\text{LST}(e, D_i') \mid e \in E\}$, referred to as the current instance of $D_i'$. Observe that $\text{LST}(D_i')$ is a normal instance of $R_i$, carrying no currency orders. For any $D'' \in \text{Mod}(S)$, we define $\text{LST}(D'') = \{\text{LST}(D_{(i,j)}) \mid D'_{(i,j)} \in D''\}$, the set of all current instances.

**Example 2.4:** Recall the completion $D_0'$ of $S_0$ from Example 2.3. Then $\text{LST}(D_0') = \{\text{LST}(\text{Emp}), \text{LST}(\text{Dept})\}$, where $\text{LST}(\text{Emp}) = \{s_1, s_4, s_5\}$, and $\text{LST}(\text{Dept}) = \{t_1\}$. Note that $\text{LST}(\text{Emp})$ and $\text{LST}(\text{Dept})$ are normal instances.

**Evaluating queries with current values.** Consider a query $Q$ posed on normal instances of $(R_1, \ldots, R_l)$, which does not refer to currency orders, where $R_i$ is in specification $S$ for $i \in [1, l]$. We say that a tuple $t$ is a certain current answer to $Q$ w.r.t. $S$ if $t$ is in

$$\bigcap_{D'' \in \text{Mod}(S)} Q(\text{LST}(D'')),$$

That is, $t$ is warranted to be an answer computed from the current values no matter how the partial currency orders in $S$ are completed, as long as the denial constraints and constraints imposed by the copy functions of $S$ are satisfied.

**Example 2.5:** Recall queries $Q_1, Q_2, Q_3$, and $Q_4$ from Example 1.1, and specification $S_0$ from Example 2.3. One can
verify that answers to the queries given in Example 1.1 are certain current answers w.r.t. $S_0$, i.e., the answers remain unchanged in $\text{LST}(D')$ for all $D' \in \text{Mod}(S_0)$. □

We summarize notations in Table 2, including those given in this section and notations to be introduced in Section 5.

### 3. Decision Problems for Data Currency

We study four problems associated with data currency.

The consistency of specifications. The first problem is to decide whether a given specification $S$ makes sense, i.e., whether there exists any consistent completion of $S$. As shown in Example 2.3, there exist specifications $S$ such that $\text{Mod}(S)$ is empty, because of the interaction between denial constraints and copy functions, among other things.

- **Example 3.1:** Consider specification $S_0$ of Example 2.3. We want to know whether every completion $D' \in \text{Mod}(S_0)$ is a certain current instance of $D'$. To this end we construct a currency order $O_t = (\text{Emp}, <\text{fn}, <\text{larger}, <\text{address}, <\text{salary}, <\text{status})$, in which $s_j <\text{salary} s_3$ is in $<\text{salary})$, but the partial orders for all other attributes are empty. One can verify that $O_t$ is indeed a certain currency order, as asserted by denial constraint $\varphi_1$.

Similarly, one can define a currency order $O_t'$ to check whether $t_4 <_{\text{emp} \cap t_4}$ is entailed by all $D' \in \text{Mod}(S_0)$. One can readily verify that it is not the case. Indeed, there exists $D'_1 \in \text{Mod}(S_0)$ such that $t_4 <_{\text{emp} \cap t_4}$ is given in $D'_1$. □

Certain current instances. Given a specification $S$ of data currency, one naturally wants to know whether every consistent completion of $S$ yields the same current instances. We say that a specification $S$ of data currency is deterministic for current instances if for all consistent completions $D'_1$, $D'_2 \in \text{Mod}(S)$, $\text{LST}(D'_1) = \text{LST}(D'_2)$. This definition naturally carries over to a particular relation schema $R$: specification $S$ is said to be deterministic for current $R$ instances if for all consistent completions $D'_1$, $D'_2 \in \text{Mod}(S)$, the instance of $R$ in $\text{LST}(D'_1)$ is equal to the instance of $R$ in $\text{LST}(D'_2)$.

- **Example 3.2:** The specification $S_0$ of Example 2.3 is deterministic for current $\text{Emp}$ instances. Indeed, for all $D' \in \text{Mod}(S_0)$, if $D'_{\text{emp}}$ is the completion of the $\text{Emp}$ instance in $D'$, then $\text{LST}(D'_{\text{emp}}) = \{s_3, s_4, s_5\}$. □

### 4. Reasoning about the Currency of Data

In this section we focus on $\text{CPS}$, $\text{COP}$, $\text{DCIP}$ and $\text{CCQA}$. We establish the data complexity and combined complexity of these problems. For the data complexity, we fix denial constraints and queries (for $\text{CCQA}$), and study the complexity in terms of varying size of data sources and copy functions. For the combined complexity we also allow denial constraints and queries to vary (see, e.g., [1] for a detailed discussion of data and combined complexity).

The consistency of specifications. We start with $\text{CPS}$, which is to decide, given a specification $S$ consisting of partial currency orders, denial constraints and copy functions, whether there exists any consistent completion in $\text{Mod}(S)$.

The result below tells us the following. (1) The problem is nontrivial: it is $\Sigma^p_2$-complete. It remains intractable when denial constraints are fixed (data complexity). (2) Denial constraints are a major factor that makes the problem hard. Indeed, the complexity bounds are not affected even when no copy functions are defined in $S$.

- **Theorem 4.1:** For $\text{CPS}$, (1) the combined complexity is $\Sigma^p_2$-complete, and (2) the data complexity is $\text{NP}$-complete. The upper bounds and lower bounds remain unchanged even in the absence of copy functions. □

- **Proof sketch:** (1) Lower bounds. For the combined complexity, we show that $\text{CPS}$ is $\Sigma^p_2$-hard by reduction from the $\exists \forall^3 \text{SAT}$ problem, which is $\Sigma^p_2$-complete (cf. [28]). Given a sentence $\phi = \exists X \forall Y \psi(X, Y)$, we construct a specification $S$ consisting of a single temporal instance $D_t$ of a binary relation schema and a set $\Gamma$ of denial constraints, such that $\phi$ is true iff $\text{Mod}(S) \neq \emptyset$. We use $D_t$ to encode truth assignments $\mu_X$ for $X$, and $\Gamma$ to assure that $\mu_X$ satisfies $\forall Y \psi(X, Y)$ if there exists a consistent completion of $D_t$. Here $\forall Y \psi(X, Y)$ is encoded by leveraging the property $\forall Y (\bigwedge_{i \in [1, r]} C_i(X, Y)) = \bigwedge_{i \in [1, r]} \forall Y C_i(X, Y)$, for $\psi(X, Y) = \bigwedge_{i \in [1, r]} C_i(X, Y)$. □
For the data complexity, we show that CPS is NP-hard by reduction from the Betweenness problem, which is NP-complete (cf. [18]). Given two sets \( E = \{ (e_i, e_j, e_k) \} \) \( e_i, e_j, e_k \in E \), the Betweenness problem is to decide whether there is a bijection \( \pi : E \rightarrow \{ 1, \ldots, |E| \} \) such that for each \( (e_i, e_j, e_k) \in E \), either \( \pi(e_i) < \pi(e_j) < \pi(e_k) \) or \( \pi(e_k) < \pi(e_j) < \pi(e_i) \). Given \( E \) and \( F \), we define a specification \( S \) with a temporal instance \( D_0 \) of a 4-ary schema, and a set of fixed denial constraints. We show that there exists a solution to the Betweenness problem iff \( \text{Mod}(S) \) is nonempty.

(2) Upper bounds. We provide an algorithm that, given a specification \( S \), guesses a completion \( D^e \) of total orders in \( S \), and then checks whether \( D^e \in \text{Mod}(S) \). The checking involves (a) denial constraints and (b) the copying condition and \( \leftarrow \)-compatibility of copy functions in \( S \). Step (b) is in \( \text{PTIME} \). Step (a) is in \( \text{PTIME} \) if the denial constraints are fixed, and it uses an NP-oracle otherwise. Hence CPS is in \( \text{NP} \) for data complexity and in \( \Sigma_2^p \) for combined complexity.

In the proofs for the lower bounds, no copy functions are defined, and the relation schemas are fixed.

The certainty of currency orders. We next study COP and DCIP. The certain currency ordering problem COP is to determine, given a specification \( S \) and a currency order \( O_t \), whether each \( t <_A s \) in \( O_t \) is entailed by the partial currency orders, denial constraints and copy functions in \( S \). The deterministic current instance problem DCIP is to decide, given \( S \), whether the current instance of each temporal instance of \( S \) is unchanged for all consistent completions of \( S \). These problems are, unfortunately, also beyond reach in practice.

Corollary 4.2: For both COP and DCIP, (1) the combined complexity is \( \Pi_2^p \)-complete, and (2) the data complexity is co\( \text{NP} \)-complete. The complexity bounds remain unchanged when no copy functions are present.

Proof sketch: (1) Lower bounds. For both COP and DCIP, the lower bounds are verified by reduction from the complement of CPS, for data complexity and combined complexity.

(2) Upper bounds. A non-deterministic algorithm is developed for each of COP and DCIP, which is in co\( \text{NP} \) (data complexity) and \( \Pi_2^p \) (combined complexity).

Query answering. The certain currency query answering problem \( \text{CCQA}(L_Q) \) is to determine, given a tuple \( t \), a specification \( S \) and a query \( Q \in L_Q \), whether \( t \in Q \{ \text{LST}(D^e) \} \) for all \( D^e \in \text{Mod}(S) \). The result below provides the data complexity of the problem, as well as its combined complexity when \( L_Q \) ranges over \( \text{CQ}, \text{UCQ}, \text{EFO}^+ \) and \( \text{FO} \). It tells us the following. (1) Disjunctions in \( \text{UCQ} \) and \( \text{EFO}^+ \) do not incur extra complexity to \( \text{CCQA} \). Indeed, \( \text{CCQA} \) has the same complexity for \( \text{CQ} \) as for \( \text{UCQ} \) and \( \text{EFO}^+ \). (2) In contrast, the presence of negation in \( \text{FO} \) complicates the analysis. (3) Copy functions have no impact on the complexity bounds.

Theorem 4.3: The combined complexity of \( \text{CCQA}(L_Q) \) is
- \( \Pi_2^p \)-complete when \( L_Q \) is \( \text{CQ}, \text{UCQ} \) or \( \text{EFO}^+ \), and
- \( \text{PSPACE}\)-complete when \( L_Q \) is \( \text{FO} \).

The data complexity is co\( \text{NP} \)-complete when \( L_Q \in \{ \text{CQ}, \text{UCQ}, \text{EFO}^+, \text{FO} \} \). These complexity bounds are unchanged in the absence of copy functions.

Proof sketch: Lower bounds. For the combined complexity, we show the following: (a) \( \text{CCQA} \) is already \( \Pi_2^p \)-hard for \( \text{CQ} \), and (b) it is \( \text{PSPACE} \)-hard for \( \text{FO} \).

(a) For \( \text{CQ} \), we verify it by reduction from the \( v^* \text{E}^3 \text{SAT} \) problem, which is \( \Pi_2^p \)-complete (cf. [28]). Given a sentence \( \phi = \exists X \forall Y \psi(X,Y) \), we define a \( \text{CQ} \) query \( Q \), a fixed tuple \( t \), and a specification \( S \) consisting of five temporal instances of fixed schemas. We use these temporal instances to encode (i) disjunction and negation, which are not expressible in \( \text{CQ} \), (ii) truth assignments \( \mu_X \) for \( X \), with an instance \( D_X \), and (iii) relations for inspecting whether \( t \) is an answer to \( Q \). Query \( Q \) encodes \( \phi \), and the relation encodes Boolean values for which there is a single completion \( D_0 \) in \( \text{Mod}(S) \). We show that \( \phi \) is true iff \( t \) is in \( Q(D_0) \).

For the data complexity, we show that \( \text{CCQA} \) is co\( \text{NP} \)-hard even for \( \text{CQ} \), by reduction from the complement of \( \text{SAT} \). Given a propositional formula \( \psi \), we define a fixed \( \text{CQ} \) query \( Q \), a fixed tuple \( t \) and a specification \( S \) consisting of two temporal instances \( D_0 \) and \( D_{\neg 0} \) of fixed relation schemas. We use \( D_0 \) to encode (i) truth assignments \( \mu_X \) for variables \( X \) in \( \psi \), and (ii) literals in \( \psi \). We encode the negations of clauses in \( \psi \) using \( D_{\neg 0} \). For \( t \), there is an unique consistent completion. For each consistent completion of \( D_0 \), i.e., each \( \mu_X \) for \( X \), query \( Q \) returns \( t \) iff \( \psi \) is not satisfied by \( \mu_X \).

In the lower bound proofs, neither denial constraints nor copy functions are defined, and all the schemas are fixed.

Upper bounds. We develop an algorithm that, given a query \( Q \), a tuple \( t \) and a specification \( S \), returns “no” if there exists \( D^e \in \text{Mod}(S) \) such that \( t \notin Q \{ \text{LST}(D^e) \} \). The algorithm first guesses \( D^e \), and then checks whether (a) \( D^e \in \text{Mod}(S) \) and (b) \( t \notin Q \{ \text{LST}(D^e) \} \). Step (b) is in \( \text{coNP} \) when \( Q \) is in \( \text{EFO}^+ \), and is in \( \text{PSPACE} \) if \( Q \) is in \( \text{FO} \). When \( Q \) is in \( \text{FO} \), step (b) is in \( \text{PTIME} \) no matter whether \( Q \) is in \( \text{CQ} \) or \( \text{FO} \). Putting these together with Theorem 4.1 (for step (a)), we conclude that the data complexity of \( \text{CCQA} \) is in \( \text{coNP} \), and its combined complexity is in \( \Pi_2^p \) for \( \text{EFO}^+ \) and in \( \text{PSPACE} \) for \( \text{FO} \).

Special cases. The results above tell us that it is nontrivial to reason about data currency. In light of this, we look into special cases of these problems with lower complexity. As shown by Theorem 4.1 and Corollary 4.2, denial constraints make the analyses of CPS, COP and DCIP intricate. Indeed, these problems are intractable even when denial constraints are fixed. Hence we consider specifications with no denial constraints, but containing partial currency orders and copy functions. The result below shows that the absence of denial constraints indeed simplifies the analyses.

Theorem 4.4: In the absence of denial constraints, CPS, COP and DCIP are in \( \text{PTIME} \).

Proof sketch: For CPS, we develop an algorithm that, given a specification \( S \) with no denial constraints defined, checks whether \( \text{Mod}(S) \neq \emptyset \). Let \( \rho \) denote the collection of copy functions in \( S \). One can verify that in the absence of denial constraints, \( S \) is consistent iff there exists no violation of the copying condition or \( \leftarrow \)-compatibility of \( \rho \) in any temporal instance of \( S \). Hence it suffices to detect violations in the instances of \( S \), rather than in their completions.
As shown in Example 2.2, it is not straightforward to check \( \prec \)-compatibility, especially when tuples are imported indirectly from other sources. Nonetheless, we show that this can be done in \( O(|S|^2) \) time, where \( |S| \) is the size of \( S \).

For \( \text{COP} \), we show that given a specification \( S \) without denial constraints, to decide whether a currency order is contained in all completions of \( S \), it suffices to check temporal instances of \( S \). This can be decided by a variation of the algorithm for \( \text{CPS} \), also in \( \text{PTIME} \); similarly for \( \text{DCIP} \).

In contrast, the absence of denial constraints does not make our lives easier when it comes to \( \text{CCQA} \). Indeed, in the proof of Theorem 4.3, the lower bounds of \( \text{CCQA} \) are verified using neither denial constraints nor copy functions.

**Corollary 4.5:** In the absence of denial constraints, \( \text{CCQA}(L_Q) \) remains coNP-hard (data complexity) and

- \( \Pi^p_2 \)-hard (combined complexity) even for \( Q \), and
- \( \text{PSPACE} \)-hard (combined complexity) for \( FO \).

Theorem 4.3 tells us that the complexity of \( \text{CCQA} \) for \( Q \) is rather robust: adding disjunctions does not increase the complexity. We next investigate the impact of removing Cartesian product from \( \text{CQ} \) on the complexity of \( \text{CCQA} \). We consider \( \text{SP} \) queries, which are \( \text{CQ} \) queries of the form

\[
Q(\bar{x}) = \exists \bar{y} \left( R(e, \bar{x}, \bar{y}) \land \psi \right),
\]

where \( \psi \) is a conjunction of equality atoms and \( \bar{x} \) and \( \bar{y} \) are disjoint sequences of variables in which no variable appears twice. \( \text{SP} \) queries support projection and selection only. For instance, \( Q_1 \) and \( Q_2 \) of Example 1.1 are \( \text{SP} \) queries. \( \text{SP} \) queries in which \( \psi \) is a tautology are referred to as *identity queries*.

We show that for \( \text{SP} \) queries, denial constraints make a difference. Without denial constraints, \( \text{CCQA} \) is in \( \text{PTIME} \) for \( \text{SP} \) queries. In contrast, when denial constraints are imposed, \( \text{CCQA} \) is no easier for identity queries than \( \exists \forall \text{FO} \).

**Corollary 4.6:** For \( \text{SP} \) queries, \( \text{CCQA}(\text{SP}) \) is

- in \( \text{PTIME} \) in the absence of denial constraints, and
- coNP-complete (data complexity) and \( \Pi^p_2 \)-complete (combined complexity) in the presence of denial constraints, even for identity queries.

**Proof sketch:** (1) In the absence of denial constraints, one can verify that for any specification \( S \) and each \( \text{SP} \) query \( Q \), \( \text{Mod}(S) \) \( \text{Q}(\text{LST}(\text{D}')') \) can be obtained from (1) evaluating \( Q \) on a representation \( \text{repr}(S) \) of \( \{\text{LST}(\text{D}')' \mid \text{D}' \in \text{Mod}(S) \} \), where \( \text{repr}(S) \) compactly represents all possible latest values by special symbols; and (2) by removing all tuples in \( Q(\text{repr}(S)) \) that contain such special symbols. Capitalizing on this property, we develop an algorithm that takes as input an \( \text{SP} \) query \( Q \), a tuple \( t \) and a specification \( S \) without denial constraints. It checks whether \( t \) is a certain answer to \( Q \) w.r.t. \( S \) as follows: (a) check whether \( S \) is consistent, and return “no” if not; (b) compute the representation \( \text{repr}(S) \); (c) check whether \( t \) is in the “stripped” version of \( Q(\text{repr}(S)) \); and (d) return “yes” if so, and “no” otherwise. Step (c) is \( \text{PTIME} \) for \( \text{SP} \) queries. By Theorem 4.4 and by leveraging the certain order computed by the algorithm for \( \text{CPS} \), steps (a) and (b) are also in \( \text{PTIME} \). Therefore, \( \text{CCQA} \) is in \( \text{PTIME} \) in this setting, for both combined complexity (when queries are not fixed) and data complexity.

(2) In the presence of denial constraints, we show that \( \text{CCQA} \) is coNP-hard (data complexity) and \( \Pi^p_2 \)-hard (combined complexity) by reduction from the complement of \( \text{CPS} \), for which the complexity is established in Theorem 4.1. Given a specification \( S \), we construct a specification \( S' \), a tuple \( t \) and an identity query \( Q \) such that \( \text{Mod}(S) = \text{empty impl} \ t \) is in \( \{\text{LST}(\text{D}')' \} \) for each \( \text{D}' \in \text{Mod}(S') \). The upper bounds of \( \text{CCQA} \) is this setting follow from Theorem 4.3.

## 5. Currency Preservation in Data Copying

As we have seen earlier, copy functions tell us what data values in a relation have been imported from other data sources. Naturally we want to leverage the imported values to improve query answers. This gives rise to the following questions: do the copy functions import sufficient current data values for answering a query \( Q \)? If not, how do we extend the copy functions such that \( Q \) can be answered with more up-to-date data values? To answer these questions we introduce a notion of currency-preserving copy functions.

We consider a specification \( S \) of data currency consisting of two collections of temporal instances (data sources) \( \text{D} = (D_1, \ldots, D_p) \) and \( \text{D}' = (D'_1, \ldots, D'_q) \), with \( (1) \) a set \( \Sigma \), (resp. \( \Sigma_j' \)) of denial constraints on \( D_i \) for each \( i \in [1,p] \) (resp. \( D'_j \) for \( j \in [1,q] \)), and (2) a collection \( \text{p} \) of copy functions \( p_{i,j} \) that imports tuples from \( D'_j \) to \( D_i \), for each \( i \in [1,p] \) and \( j \in [1,q] \), i.e., all the functions of \( \text{p} \) import data from \( D'_j \) to \( D_i \).

### Extensions

To formalize currency preservation, we first present the following notions. Assume that \( D_i = (D_i, \prec, A_i, \ldots, A_m) \) are temporal instances of relation schemas \( R_i = (EID, A_1, \ldots, A_n) \) and \( R'_j = (EID, B_1, \ldots, B_m) \), respectively. Assume that \( n \leq m \).

An *extension* of \( D_i \) is a temporal instance \( D'_i = (D'_i, \prec, A'_1, \ldots, A'_m) \) of \( D_i \) such that (1) \( D \subseteq D'_i \), (2) \( \prec_A \subseteq \prec_{A'_i} \) for all \( h \in [1,n] \), and (3) \( \text{rep}(D_i) = \text{rep}(D'_i) \). Intuitively, \( D'_i \) extends \( D_i \) by adding new tuples for those entities that are already in \( D_i \). It does not introduce new entities.

Consider two copy functions: \( p_{i,j} \) imports tuples from \( D'_j \) to \( D_i \), and \( p_{i,j}' \) from \( D'_j \) to \( D_i' \), both of signature \( R_i[A] \rightarrow R_i'[B] \), where \( A = (A_1, \ldots, A_n) \) and \( B \) is a sequence of \( n \) attributes in \( R'_i \). We say that \( p_{i,j} \) extends \( p_{i,j}' \) if

1. \( D'_i \) is an extension of \( D_i \);
2. for each tuple \( t \in D_i \), if \( p_{i,j}(t) \) is defined, then so is \( p_{i,j}'(t) \) and moreover, \( p_{i,j}(t) = p_{i,j}'(t) \);
3. for each tuple \( t \in D'_i \setminus D_i \), there exists a tuple \( s \) in \( D_j' \) such that \( p_{i,j}(t) = s \).

We refer to \( D'_i \) as the *extension of \( D_i \) by \( p_{i,j} \)*.

Observe that \( D'_i \) is not allowed to expand arbitrarily. (a) Each new tuple in \( D'_i \) is copied from a tuple \( s \) in \( D'_j \). (b) No new entity is introduced. Note that only copy functions that cover all attributes but \( \text{EID} \) of \( R_i \) can be extended. This assures that all the attributes of a new tuple are in place.

An *extension* \( \mathbf{p} \) of \( \mathbf{p} \) is a collection of copy functions \( p_{i,j} \) such that \( \mathbf{p} \neq \mathbf{p} \) and moreover, for all \( i \in [1,p] \) and \( j \in [1,q] \), either \( p_{i,j} \) is an extension of \( p_{i,j}' \) or \( p_{i,j}' \) is an extension of \( p_{i,j} \).

We denote the set of all extensions of \( \mathbf{p} \) by \( \text{Ext}(\mathbf{p}) \).

For each \( \mathbf{p} \) in \( \text{Ext}(\mathbf{p}) \), we denote as \( S' \) the *extension of \( S \) by \( \mathbf{p} \)*, which consists of the same \( \text{D}' \) and denial constraints as \( S \), but has copy functions \( \mathbf{p} \) and \( \text{D}' = (D'_1, \ldots, D'_q) \), as \( \text{D}' \) is an extension of \( D_i \) by \( p_{i,j} \) for all \( j \in [1,q] \).

### Currency preservation

We are now ready to define currency preservation. Consider a collection \( \mathbf{p} \) of copy functions
FN | LN | address | salary | status | phone
---|---|---|---|---|---
S′₁ | Mary | Dupont | 6 Main St | 60k | married | 6671975
S′₂ | Mary | Dupont | 6 Main St | 80k | married | 6671975
S′₃ | Mary | Smith | 2 Small St | 80k | divorced | 2962845

Figure 2: Relation Mgr

in a specification S. We say that \( \mathcal{P} \) is currency preserving for a query \( Q \) w.r.t. S if (a) \( \text{Mod}(S) \neq \emptyset \), and moreover, (b) for all \( \mathcal{P} \in \text{Ext}(\mathcal{P}) \) such that \( \text{Mod}(\mathcal{P}) \neq \emptyset \), we have that

\[
\bigcap_{\mathcal{D}' \subseteq \text{Mod}(\mathcal{S})} \{Q(\text{LST}(\mathcal{D}''))\} = \bigcap_{\mathcal{D}' \subseteq \text{Mod}(\mathcal{S})} \{Q(\text{LST}(\mathcal{D}''))\}.
\]

Intuitively, \( \mathcal{P} \) is currency preserving if (1) \( \mathcal{P} \) is meaningful; and (2) for each extension \( \mathcal{P}' \) of \( \mathcal{P} \) that makes sense, the certain current answers to \( Q \) are not improved by \( \mathcal{P}' \), i.e., no matter what additional tuples are imported for those entities in \( \mathcal{D} \), the certain current answers to \( Q \) remain unchanged.

Example 5.1: As shown in Fig. 2, relation Mgr collects manager records. Consider a specification \( S_1 \) consisting of the following: (a) temporal instances Mgr of Fig. 2 and Emp of Fig. 1, in which partial currency orders are \( \emptyset \) for all attributes; (b) denial constraints \( \varphi_1, \varphi_2 \) of Example 2.1 and \( \varphi_3: \forall s.t. (s[EID] = t[EID] \land s[status] = \text{"divorced"} \land t[status] = \text{"married"}) \rightarrow t[LN] = s[LN] \), i.e., if \( s[status] \) is divorced and \( t[status] \) is married, then \( s \) is more current than \( t \) in \( LN \); and (c) a copy function \( \rho \) with signature \( \text{Emp}[\overline{A}] \leftarrow \text{Mgr}[\overline{A}] \), where \( \overline{A} = \langle \text{FN}, \text{LN}, \text{address}, \text{salary}, \text{status} \rangle \), such that \( \rho(s_3) = s_2 \), i.e., \( s_3 \) of Emp is copied from \( s_2 \) of Mgr. Obviously \( S_1 \) is consistent.

Recall query \( Q_2 \) of Example 1.1, which is to find Mary’s current last name. For \( Q_2 \), \( \rho \) is not currency preserving. Indeed, there is an extension \( \mathcal{P}_1 \) of \( \rho \) by copying \( s'_1 \) to Emp. In all consistent completions of the extension \( \mathcal{Ext}_1 \) of Emp by \( \mathcal{P}_1 \), the answer to \( Q_2 \) is Smith. However, the answer to \( Q_2 \) in all consistent completions of Emp is Dupont (see Examples 1.1 and 2.5). In contrast, \( \rho_3 \) is currency preserving for \( Q_2 \). Indeed, copying more tuples from Mgr (i.e., tuple \( s'_1 \)) to Emp does not change the answer to \( Q_2 \) in \( \mathcal{Ext}_1 \).

Deciding currency preservation. There are several decision problems associated with currency-preserving copy functions, which we shall investigate in the rest of the paper.

The first problem is to decide whether given copy functions have imported necessary current data for answering a query.

<table>
<thead>
<tr>
<th>CPP(( \mathcal{L}_Q ))</th>
<th>The currency preservation problem.</th>
</tr>
</thead>
<tbody>
<tr>
<td>INPUT: A query ( Q ) in ( \mathcal{L}_Q ), and a specification ( S ) of data currency with copy functions ( \mathcal{P} ).</td>
<td></td>
</tr>
<tr>
<td>QUESTION: Is ( \mathcal{P} ) currency preserving for ( Q )?</td>
<td></td>
</tr>
</tbody>
</table>

Minimal copying. Moreover, we want to know whether a currency preserving \( \mathcal{P} \) does not copy unnecessary or redundant data. To this end, we use \([\mathcal{P}]\) to denote the size of the sums of data values copied by \( \mathcal{P} \). We say that \( \mathcal{P} \) is minimal for \( Q \) if there exists no collection \( \mathcal{P}' \) of copy functions such that (1) \( \mathcal{P}' \in \text{Ext}(\mathcal{P'}) \), (2) \( |\mathcal{P}'| < |\mathcal{P}| \), and (3) \( \mathcal{P}' \) is currency preserving for \( Q \). That is, there exists no currency-preserving \( \mathcal{P}' \) that imports less data from \( \mathcal{D}' \) to \( \mathcal{D} \) than \( \mathcal{P} \).

<table>
<thead>
<tr>
<th>MCP(( \mathcal{L}_Q ))</th>
<th>The minimal copying problem.</th>
</tr>
</thead>
<tbody>
<tr>
<td>INPUT: ( S ) and ( \mathcal{P} ) as in CPP, with a collection ( \mathcal{P} ) of currency-preserving copy functions in ( S ).</td>
<td></td>
</tr>
<tr>
<td>QUESTION: Is ( \mathcal{P} ) minimal for ( Q )?</td>
<td></td>
</tr>
</tbody>
</table>

Extending copy functions. Consider a consistent specification \( S \) in which \( \mathcal{P} \) is not currency preserving for a query \( Q \). The next problem is to decide whether \( \mathcal{P} \) in \( S \) can be extended to be currency preserving for \( Q \).

<table>
<thead>
<tr>
<th>ECP(( \mathcal{L}_Q ))</th>
<th>The existence problem.</th>
</tr>
</thead>
<tbody>
<tr>
<td>INPUT: A query ( Q ) in ( \mathcal{L}_Q ), and a consistent specification ( S ) with non-currency-preserving ( \mathcal{P} ).</td>
<td></td>
</tr>
<tr>
<td>QUESTION: Does there exist ( \mathcal{P}' \in \text{Ext}(\mathcal{P}) ) that is currency preserving for ( Q )?</td>
<td></td>
</tr>
</tbody>
</table>

Bounds extension. We also want to know whether it suffices to extend \( \mathcal{P} \) by copying additional data of a bounded size, and make it currency preserving.

<table>
<thead>
<tr>
<th>BCP(( \mathcal{L}_Q ))</th>
<th>The bounded copying problem.</th>
</tr>
</thead>
<tbody>
<tr>
<td>INPUT: ( S ), ( \mathcal{P} ) and ( Q ) as in ECP, and a positive number ( k ).</td>
<td></td>
</tr>
<tr>
<td>QUESTION: Does there exist ( \mathcal{P}' \in \text{Ext}(\mathcal{P}) ) such that (</td>
<td>\mathcal{P}'</td>
</tr>
</tbody>
</table>

6. Deciding Currency Preservation

We next study the decision problems in connection with currency-preserving copy functions, namely, CPP(\( \mathcal{L}_Q \)), MCP(\( \mathcal{L}_Q \)), ECP(\( \mathcal{L}_Q \)) and BCP(\( \mathcal{L}_Q \)) when \( \mathcal{L}_Q \) is CQ, UCQ, \( \exists \text{FO}^+ \) or FO. We provide their combined complexity and data complexity, and identify special cases with lower complexity.

Checking currency preservation. We first investigate CPP(\( \mathcal{L}_Q \)), the problem of deciding whether a collection of copy functions in a given specification is currency preserving for a query \( Q \). We show that CPP is nontrivial. Indeed, its combined complexity is already \( \Pi^P \)-hard when \( \mathcal{L}_Q \) is in CQ, and it is PSPACE-complete when \( \mathcal{L}_Q \) is in FO.

One might be tempted to think that fixing denial constraints would make our lives easier. Indeed, in practice denial constraints are often predefined and fixed, and only data, copy functions and query vary. Moreover, as shown in Theorem 4.1 for the consistency problem, fixing denial constraints indeed helps there. Unfortunately, it does not simplify the analysis of the combined complexity when it comes to CPP. Even when both query and denial constraints are fixed, the problem is \( \Pi^P \)-complete (data complexity).

Theorem 6.1: For CPP(\( \mathcal{L}_Q \)), the combined complexity is

- \( \Pi^P \)-complete when \( \mathcal{L}_Q \) is CQ, UCQ or \( \exists \text{FO}^+ \), and
- PSPACE-complete when \( \mathcal{L}_Q \) is FO.
- Its data complexity is \( \Pi^P \)-complete when \( \mathcal{L}_Q \in \{\text{CQ, UCQ, } \exists \text{FO}^+, \text{FO}\} \).

The combined complexity bounds remain unchanged when denial constraints and copy functions are fixed.

Proof sketch: (1) Lower bounds. For the combined complexity, it suffices to show that CPP is already \( \Pi^P \)-hard for CQ, while for FO, it is PSPACE-hard. For the data complexity, we show that CPP is \( \Pi^P \)-hard with CQ queries. The \( \Pi^P \) lower bound is verified by reduction from the \( \forall \exists \forall^* 3\text{SAT} \) problem, which is \( \Pi^P \)-complete [cf. [28]]. Given a sentence \( \phi = \forall X \exists Y \forall Z \psi(X,Y,Z) \), we construct a query \( Q \) in CQ, and a specification \( S \) with (i) two data sources \( D \) and \( D' \), (ii) a single copy function \( \rho \) and (iii) a set of denial constraints. Source \( D \) consists of four relations encoding Boolean values, disjunction, conjunction and negation, as well as a relation \( D_b \) for testing certain current query answers. Source \( D' \) has a single relation \( D_b \) from which some tuples are copied to \( D_b \) by \( \rho \). Query \( Q \) encodes \( \phi \) by leverag-
ing the relations in $D$ for Boolean operations, and the property of $\forall\exists \psi(X,Y,Z)$ explored in the proof of Theorem 4.1. We show that $\phi$ is true if $p$ is currency preserving for $Q$.

When it comes to FO, we show that CPP is PSPACE-hard by a straightforward reduction from $Q3SAT$.

In these proofs, both denial constraints and copy functions are fixed, independent of $\forall^3 \exists^3 3SAT$ or $Q3SAT$ instances.

For the data complexity, we verify the $\Pi_2^p$ lower bound for CQ by reduction from the $\forall^3 \exists^3 3SAT$ problem. Given a sentence $\phi = \exists X \forall Y \exists Z \psi(X,Y,Z)$, we define a query $Q$ in CQ and a specification $S$ such that $\phi$ is true iff $p$ is currency preserving for $Q$ w.r.t. $S$. Hence the decision problem $ECP$ is in $O(1)$ time, although it may take much longer time to explicitly construct a currency-preserving extension of $\tilde{\rho}$.

Proposition 6.3: $ECP(L_Q)$ is decidable in $O(1)$ time for both the combined complexity and data complexity, when $L_Q$ is CQ, UCQ, $\exists FO^+$ or FO.

Proof sketch: To show the existence of currency-preserving extensions of $p$, we give an algorithm to construct one. Let $D'$ be the data source in $S$ from which tuples can be copied. For all copy function $p$ in $\tilde{\rho}$, if $p$ can be extended, the algorithm expands $p$ by copying tuples one by one from $D'$, starting from the most current ones, as long as the extended instances satisfy the denial constraints in $S$ and the constraints of the copy functions. It proceeds until no more tuples from $D'$ can be copied while satisfying the constraints, and yields a currency-preserving extension of $\tilde{\rho}$.

Bounded extensions. In contrast to ECP, when it comes to deciding whether $\tilde{\rho}$ can be made currency-preserving by copying data within a bounded size, the analysis becomes far more intricate. Indeed, the result below tells us that even for CQ, BCP is $\Sigma^p_3$-hard, and fixing denial constraints and copy functions does not help. When both queries and denial constraints are fixed, BCP is $\Sigma^p_3$-complete.

For $BCP(L_Q)$, the combined complexity is
- $\Sigma^p_3$-complete when $L_Q$ is CQ, UCQ or $\exists FO^+$, and
- PSPACE-complete when $L_Q$ is FO.
- Its data complexity is $\Sigma^p_3$-complete when $L_Q \in \{CQ, UCQ, \exists FO^+, FO\}$.

The combined complexity bounds remain unchanged when denial constraints and copy functions are fixed.

Proof sketch: (1) Lower bounds. For FO, the proofs are similar to their counterparts of CPS. For CQ queries, we show that $MCP(L_Q)$ is $\Sigma^p_3$-hard (combined complexity) by reduction from the MSA($\forall^3 \exists^3 3SAT$) problem, which is $\Sigma^p_3$-complete [26]. The latter problem is to determine, given a satisfiable sentence $\phi = \exists X \forall Y \exists Z \psi(X,Y,Z)$, whether in the lexicographically maximum truth assignment $\mu_X$ for variables in $X$ such that $VY \exists Z \psi(\mu_X(x_1), \ldots, \mu_X(x_n), Y,Z)$ evaluates to true, the last variable $x_n \in X$ has value 1, i.e., whether $\mu_X(x_n) = 1$. For the data complexity, we verify that it is $\Pi_2^p$-hard for CQ by reduction from MSA($\forall^3 \exists^3 3SAT$)-problem. These reductions need to encode the lexicographical successor function for variables in $X$, and are more involved than those given in the proof of Theorem 6.1.

(2) Upper bounds. We provide an algorithm that takes as input a query $Q$ and a specification $S$ with currency-preserving copy functions $\tilde{\rho}$. For each tuple $t$ copied by $\tilde{\rho}$, it checks whether removing $t$ makes the copy functions not currency preserving, by using the algorithm for CPP in the proof of Theorem 6.1 as an oracle. Hence $MCP$ is in $\Delta^p_2$ (combined complexity) and in $\Delta^p_3$ (data complexity).

The feasibility of currency preservation. We now consider $ECP(L_Q)$. It is to decide, given a query $Q$ and a specification $S$ in which copy functions $\tilde{\rho}$ are not currency preserving for $Q$, whether we can extend $\tilde{\rho}$ to preserve currency.

The good news is that the answer to this question is affirmative: we can always extend $\tilde{\rho}$ and make them currency preserving for $Q$. Hence the decision problem $ECP$ is in $O(1)$ time, although it may take much longer time to explicitly construct a currency-preserving extension of $\tilde{\rho}$.

For $CQ(L_Q)$, we show that $\Sigma^p_3$-complete when $L_Q$ is CQ, UCQ or $\exists FO^+$, and
- PSPACE-complete when $L_Q$ is FO.
- Its data complexity is $\Sigma^p_3$-complete when $L_Q \in \{CQ, UCQ, \exists FO^+, FO\}$.

The combined complexity bounds remain unchanged when denial constraints and copy functions are fixed.

Proof sketch: (1) Lower bounds. For FO, we show that $BCP$ is PSPACE-hard by a simple reduction from $Q3SAT$. For CQ, we show that $BCP$ is $\Sigma^p_3$-hard by reduction from the $\forall^3 \exists^3 3SAT$ problem, which is $\Sigma^p_3$-complete (cf. [28]). Given a sentence $\phi = \exists X \forall Y \exists Z \psi(X,Y,Z)$, we define a CQ query $Q$, a positive number $k$ and a specification $S$ with two copy functions $\tilde{\rho}$. We show that $\phi$ is true if there exists a extension $\rho^*$ of $\tilde{\rho}$ such that $|\rho^*| \leq |\rho| + k$ and $\rho^*$ is currency preserving for $Q$. For $\Sigma^p_3$, we use temporal instances in $S$ to encode disjunction and negation, which $Q$ leverages to express $\phi$. We also define a data source in $S$ whose current instance ranges over all truth assignments for $W$, and use the data source to inspect possible extensions of $\rho$.

For the data complexity, we verify the $\Sigma^p_3$ lower bound for CQ by reduction from the $\forall^3 \exists^3 3SAT$ problem. This reduction is more involved than the one developed for the combined complexity. Given an $\forall^3 \exists^3$ sentence $\phi$, we define a query $Q$ in CQ that is independent of $\phi$ but nonetheless, is able to encode the negations of the clauses in $\phi$, by making use of temporal instances in a specification constructed.

In all these proofs, denial constraints and copy functions are independent of input sentences, i.e., they are fixed.

(2) Upper bounds. We develop an algorithm for BCP, which first guesses an extension $\rho^*$ of $\tilde{\rho}$ that copies more data of a
bounded size, and then checks whether $\tilde{\rho}$ is currency preserving, by invoking the algorithm for CPP. From Theorem 6.1 the upper bounds for BCP follow immediately. □

Special cases. Theorem 6.1, 6.2 and 6.4 motivate us to explore special cases that simplify the analyses. In contrast to Theorem 4.1 and Corollary 4.2, we have seen that fixing denial constraints does not make our lives easier when it comes to CPP, MCP or BCP. However, when denial constraints are absent, these problems become tractable for SP queries. This is consistent with Corollary 4.6.

Theorem 6.5: When denial constraints are absent, for SP queries both the combined complexity and the data complexity are in PTIME for CPP, MCP and BCP (when the bound $k$ on the size of additional data copied is fixed). □

Proof sketch: (1) CPP. We develop a PTIME algorithm $A$ that runs as input a specification $S$ and an SP query $Q$ defined on instances of a relation schema $R$. It checks whether the copy functions $\tilde{\rho}$ in $S$ are currency preserving for $Q$. The main idea behind $A$ is as follows. Let $E$ be the set of all entities in $D_i$, where $D_i$ is the temporal instance of $R$ in $S$. Let $C$ be the set of all current answers to $Q$. By Corollary 4.6, $C$ can be computed in PTIME. For each $e \in E$, $A$ inspects tuples $t$ in $D'(e)$ one by one, to find whether it would “spoil” some answer $s \in C$ produced by the current tuple of $e$ if $t$ were imported, i.e., adding $t$ would make $LST(e;D'(e))$ either empty or a distinct tuple that does not produce $s$ via $Q$. Here $D'$ is the data source in $S$ from which tuples are copied. When denial constraints are absent and $Q$ is in SP, this can be done in PTIME. The algorithm then checks spoilers for all $e \in E$, to find whether there exists $s \in C$ spoiled by importing tuples for all entities that yield $s$, or whether some spoilers introduce a new certain current answer. This can be done in PTIME since the entities in $E$ are independent of each other. The algorithm returns “yes” if no such spoilers exist. It is in PTIME as argued above.

(2) MCP. Given $A$, an algorithm for MCP is immediate: for each “reduced” $\tilde{\rho}$ that removes one imported tuple from $\rho$, it checks whether $\tilde{\rho}$ is currency preserving for $Q$ by using $A$. The algorithm is obviously in PTIME.

(3) BCP. When the bound $k$ is fixed, there are polynomially many extensions $\tilde{\rho}$ of $\rho$ such that $|\tilde{\rho}| \leq |\rho| + k$. For each such $\tilde{\rho}$ we check whether $\tilde{\rho}$ is currency preserving for $Q$ by invoking $A$. This can be done in PTIME. □

For BCP($L_Q$), when the bound $k$ is predefined and fixed, the analysis also becomes simpler when $L_Q$ is CQ, UCQ or $\exists$FO$^+$. For FO, however, BCP remains PSPACE-complete.

Corollary 6.6: When $k$ is fixed, BCP($L_Q$) is
- $\Delta^P_2$-complete (combined) for CQ, UCQ and $\exists$FO$^+$,
- $\Delta^P_2$-complete (data) for CQ, UCQ and $\exists$FO$^+$, but is
- PSPACE-complete for FO (combined complexity).

Proof sketch: (1) Upper bounds. As remarked earlier, when $k$ is fixed there are polynomially many extensions $\tilde{\rho}$ of $\rho$ such that $|\tilde{\rho}| \leq |\rho| + k$. For each such $\tilde{\rho}$ we check whether $\tilde{\rho}$ is currency preserving, by invoking the algorithm for checking CPP given in the proof of Theorem 6.1. Therefore, BCP is in $P^{\Sigma_2} = \Delta^P_2$ for $\exists$FO$^+$ (combined complexity). Moreover, when queries and denial constraints are fixed, it is in $P^{\Sigma_2} = \Delta^P_2$ (data complexity). For FO, the CPP checking is in PSPACE, and hence so is the upper bound for BCP.

(2) Lower bounds. We show that when $k$ is fixed, BCP is already $\Delta^P_2$-hard (combined complexity) for CQ queries, by reduction from the $MSA(3^\forall \lor 3^\exists 3SAT)$ problem. In addition, we verify that it is $\Delta^P_2$-hard (data complexity) for CQ queries by reduction from the $MSA(3^\forall \lor 3^\exists 3SAT)$ problem. For FO queries, we show that it remains PSPACE-hard (combined complexity) by reduction from $Q3SAT$. □

7. Conclusions

We have proposed a model to specify the currency of data in the absence of reliable timestamps but in the presence of copy relationships. We have also introduced a notion of currency preservation to assess copy functions for query answering. We have identified eight fundamental problems associated with data currency and currency preservation (CPP, COP, DCIP, CQA($L_Q$), CPP($L_Q$), MCP($L_Q$), ECP($L_Q$) and BCP($L_Q$)). We have provided a complete picture of the lower and upper bounds of these problems, all matching, for their data complexity as well as combined complexity when $L_Q$ ranges over a variety of query languages. These results are not only of theoretical interest in their own right, but may also help practitioners distinguish current values from stale data, answer queries with current data, and design proper copy functions to import data from external sources.

The main complexity results are summarized in Tables 2 and 3, annotated with their corresponding theorems.

The study of data currency is still preliminary. An open issue concerns generalizations of copy functions. To simplify the presentation we assume a single copy function from one relation to another. Nonetheless we believe that all the results remain intact when multiple such functions coexist. For currency-preserving copy functions, we assume that the signatures “cover” all attributes (except EID) of the importing relation. It is nontrivial to relax this requirement, however, since otherwise unknown values need to be introduced for attributes whose value is not provided by the extended copy functions. A second issue is about practical use of the study. As shown in Tables 2 and 3, most of the problems are intractable. To this end we expect to (a) identify practical PTIME cases in various applications, (b) develop efficient heuristic algorithms with certain performance guarantees, and (c) conduct incremental analysis when data or copy functions are updated, which is expected to result in a lower complexity than its batch counterpart when the area affected by the updates is small, as commonly found in practice. A third issue concerns the interaction between data consistency and data currency. There is an intimate connection between these two central issues of data quality. Indeed, identifying the current value of an entity helps resolve data inconsistencies, and conversely, repairing data helps remove obsolete data. While these processes should logically be unified, we are not aware of any previous work on this topic. Finally, it is interesting to develop syntactic characterizations of currency-preserving copy functions.

Acknowledgments. Fan and Geects are supported in part by an IBM scalable data analytics for a smarter planet innovation award, and the RSE-NSFC Joint Project Scheme.

8. References

<table>
<thead>
<tr>
<th>Complexity</th>
<th>CCQA((L_Q))</th>
<th>CPP((L_Q))</th>
<th>MCP((L_Q))</th>
<th>ECP((L_Q))</th>
<th>BCP((L_Q))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data complexity</td>
<td>coNP-complete (Th 4.3)</td>
<td>(\Pi^p_2)-complete (Th 6.1)</td>
<td>(\Delta^p_3)-complete (Th 6.2)</td>
<td>(O(1)) (Prop 6.3)</td>
<td>(\Sigma^p_2)-complete (Th 6.4)</td>
</tr>
<tr>
<td>Combined complexity</td>
<td>(\Sigma^p_2)-complete (Th 4.1)</td>
<td>(\Pi^p_2)-complete (Th 6.1)</td>
<td>(\Delta^p_3)-complete (Th 6.2)</td>
<td>(O(1)) (Prop 6.3)</td>
<td>(\Sigma^p_2)-complete (Th 6.4)</td>
</tr>
<tr>
<td>Special case</td>
<td>(O(1)) (Prop 6.3)</td>
<td>(\Sigma^p_2)-complete (Th 6.4)</td>
<td>(O(1)) (Prop 6.3)</td>
<td>(\Sigma^p_2)-complete (Th 6.4)</td>
<td>(O(1)) (Prop 6.3)</td>
</tr>
<tr>
<td>Combined and data complexity</td>
<td>PTIME (Th 4.4)</td>
<td>PTIME (Th 4.4)</td>
<td>PTIME (Th 4.4)</td>
<td>PTIME (Th 4.6)</td>
<td>PTIME (Th 4.6)</td>
</tr>
</tbody>
</table>

Table 2: Complexity of problems for reasoning about data currency (CPS, COP, DCIP)

<table>
<thead>
<tr>
<th>Complexity</th>
<th>CCQA((L_Q))</th>
<th>CPP((L_Q))</th>
<th>MCP((L_Q))</th>
<th>ECP((L_Q))</th>
<th>BCP((L_Q))</th>
</tr>
</thead>
<tbody>
<tr>
<td>FO</td>
<td>(\Pi^p_2)-complete (Th 4.3)</td>
<td>(\Pi^p_2)-complete (Th 6.1)</td>
<td>(\Delta^p_3)-complete (Th 6.2)</td>
<td>(O(1)) (Prop 6.3)</td>
<td>(\Sigma^p_2)-complete (Th 6.4)</td>
</tr>
<tr>
<td>Special case</td>
<td>(O(1)) (Prop 6.3)</td>
<td>(\Sigma^p_2)-complete (Th 6.4)</td>
<td>(O(1)) (Prop 6.3)</td>
<td>(\Sigma^p_2)-complete (Th 6.4)</td>
<td>(O(1)) (Prop 6.3)</td>
</tr>
<tr>
<td>Combined &amp; data</td>
<td>PTIME (Cor 4.6)</td>
<td>PTIME (Th 4.6)</td>
<td>PTIME (Th 4.6)</td>
<td>PTIME (Th 6.5)</td>
<td>PTIME (Th 6.5)</td>
</tr>
</tbody>
</table>

Table 3: Complexity of problems for query answering and for determining currency preservation