



THE UNIVERSITY *of* EDINBURGH

## Edinburgh Research Explorer

### Inferring data currency and consistency for conflict resolution

**Citation for published version:**

Fan, W, Geerts, F, Tang, N & Yu, W 2013, Inferring data currency and consistency for conflict resolution. in *29th IEEE International Conference on Data Engineering, ICDE 2013, Brisbane, Australia, April 8-12, 2013*. Institute of Electrical and Electronics Engineers (IEEE), pp. 470-481.  
<https://doi.org/10.1109/ICDE.2013.6544848>

**Digital Object Identifier (DOI):**

[10.1109/ICDE.2013.6544848](https://doi.org/10.1109/ICDE.2013.6544848)

**Link:**

[Link to publication record in Edinburgh Research Explorer](#)

**Document Version:**

Publisher's PDF, also known as Version of record

**Published In:**

29th IEEE International Conference on Data Engineering, ICDE 2013, Brisbane, Australia, April 8-12, 2013

**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](mailto:openaccess@ed.ac.uk) providing details, and we will remove access to the work immediately and investigate your claim.



# Inferring Data Currency and Consistency for Conflict Resolution

Wenfei Fan<sup>1,4</sup>, Floris Geerts<sup>2</sup>, Nan Tang<sup>3</sup>, Wenyan Yu<sup>1</sup>

<sup>1</sup>University of Edinburgh    <sup>2</sup>University of Antwerp    <sup>3</sup>QCRI, Qatar Foundation

<sup>4</sup>Big Data Research Center and State Key Laboratory of Software Development Environment, Beihang University

wenfei@inf.ed.ac.uk, floris.geerts@ua.ac.be, ntang@qf.org.qa, wenyan.yu@ed.ac.uk

**Abstract**—This paper introduces a new approach for conflict resolution: given a set of tuples pertaining to the same entity, it is to identify a single tuple in which each attribute has the latest and consistent value in the set. This problem is important in data integration, data cleaning and query answering. It is, however, challenging since in practice, reliable timestamps are often absent, among other things. We propose a model for conflict resolution, by specifying data currency in terms of partial currency orders and currency constraints, and by enforcing data consistency with constant conditional functional dependencies. We show that identifying data currency orders helps us repair inconsistent data, and vice versa. We investigate a number of fundamental problems associated with conflict resolution, and establish their complexity. In addition, we introduce a framework and develop algorithms for conflict resolution, by integrating data currency and consistency inferences into a single process, and by interacting with users. We experimentally verify the accuracy and efficiency of our methods using real-life and synthetic data.

## I. INTRODUCTION

Conflict resolution is the process that, given a set  $I_t$  of tuples pertaining to the same entity, fuses the tuples into a single tuple and resolves conflicts among the tuples of  $I_t$  [10]. Traditional work resolves conflicts typically by taking, *e.g.*, the max, min, avg, any of attribute values (see [4] for a survey).

We study a new approach for conflict resolution, by highlighting both data currency and data consistency. Given  $I_t$ , it is to identify a single tuple in which each attribute has *consistent* and *the most current value* taken from  $I_t$ , referred to as the *true values* of the entity *relative to*  $I_t$ . The need for studying this problem is evident in data integration, where conflicts often emerge from values from different sources. It is also common to find multiple values of the same entity residing in a database. While these values were *once correct*, *i.e.*, they were the true values of the entity at some time, some of them may have become *stale* and thus *inconsistent*. Indeed, it is estimated that in a customer database, about 50% of the records may become obsolete within two years [11]. With these comes the need for resolving conflicts for, *e.g.*, data fusion [4], [10], data cleaning [1] and query answering with current values [15].

No matter how important, the problem is rather challenging. Indeed, it is already highly nontrivial to find consistent values for an entity [1], [7]. Moreover, it is hard to identify the most current entity values [15] since in the real world, reliable timestamps are often absent [23], [28]. Add to this the complication that when resolving conflicts one has to find the entity values that are *both* consistent *and* most current.

**Example 1:** The photo in Fig. 1 is known as “V-J Day in

Times Square”. The nurse and sailor in the photo have been identified as Edith Shain and George Mendonça, respectively, and their information is collected in sets  $E_1$  and  $E_2$  of tuples, respectively, shown in Fig. 2.

We want to find the true values of these entities, *i.e.*, a tuple  $t_1$  for Edith (resp. a tuple  $t_2$  for George) such that the tuple has the most current and consistent attribute values for her (resp. his) status, job, the number of kids, city, AC (area code), zip and county in  $E_1$  (resp.  $E_2$ ). However, the values in  $E_1$  ( $E_2$ ) have conflicts, and worse still, they do not carry timestamps. They do not tell us, for instance, whether Edith still lives in NY, or even whether she is still alive. □

The situation is bad, but not hopeless. We can often deduce certain currency orders from the semantics of the data. In addition, dependencies such as conditional functional dependencies (CFDs) [13] have proven useful in improving the consistency of the data. Better still, data currency and consistency interact with each other. When they are taken together, we can often infer some true values from inconsistent tuples, even in the absence of timestamps, as illustrated below.

**Example 2:** From the semantics of the data, we can deduce the *currency constraints* and CFDs shown in Fig. 3.

(1) *Currency constraints.* We know that for each person, status only changes from *working* to *retired* and from *retired* to *deceased*, but not from *deceased* to *working* or *retired*. These can be expressed as  $\varphi_1$  and  $\varphi_2$  given in Fig. 3, referred to as *currency constraints*. Here  $t_1 \prec_{\text{status}} t_2$  denotes a partial currency order on the attribute status, indicating that  $t_2$  is more current than  $t_1$  in attribute status. Similarly, we know that job can only change from *sailor* to *veteran* but not the other way around. We can express this as currency constraint  $\varphi_3$ , shown in Fig. 3. Moreover, the number of kids typically increases monotonically. We can express this as  $\varphi_4$ , assuring that  $t_2$  is more current than  $t_1$  in attribute kids if  $t_1[\text{kids}] < t_2[\text{kids}]$ .

In addition, we know that for each person, if tuple  $t_2$  is more current than  $t_1$  in attribute status, then  $t_2$  is also more current than  $t_1$  in job, AC and zip. Furthermore, if  $t_2$  is more current than  $t_1$  in attributes city and zip, it also has a more current county than  $t_1$ . These can be expressed as  $\varphi_5$ – $\varphi_8$ .

(2) *Constant CFDs.* In the US, if the AC is 213 (resp. 212), then the city must be LA (resp. NY). These are expressed as conditional functional dependencies  $\psi_1$  and  $\psi_2$  in Fig. 3.

We can apply these constraints to  $E_1$  in Fig. 2, to improve the currency and consistency of the data. By *interleaving* inferences of data currency and consistency, we can actually



Fig. 1. V-J Day

		name	status	job	kids	city	AC	zip	county
$E_1$	$r_1$ :	Edith Shain	working	nurse	0	NY	212	10036	Manhattan
	$r_2$ :	Edith Shain	retired	n/a	3	SFC	415	94924	Dogtown
	$r_3$ :	Edith Shain	deceased	n/a	null	LA	213	90058	Vermont
$E_2$	$r_4$ :	George Mendonça	working	sailor	0	Newport	401	02840	Rhode Island
	$r_5$ :	George Mendonça	retired	veteran	2	NY	212	12404	Accord
	$r_6$ :	George Mendonça	unemployed	n/a	2	Chicago	312	60653	Bronzeville

Fig. 2. Instances  $E_1$  for entity Edith and  $E_2$  for George

<i>Currency constraints:</i>	$\varphi_1: \forall t_1, t_2 (t_1[\text{status}] = \text{"working"} \wedge t_2[\text{status}] = \text{"retired"} \rightarrow t_1 \prec_{\text{status}} t_2)$ $\varphi_2: \forall t_1, t_2 (t_1[\text{status}] = \text{"retired"} \wedge t_2[\text{status}] = \text{"deceased"} \rightarrow t_1 \prec_{\text{status}} t_2)$ $\varphi_3: \forall t_1, t_2 (t_1[\text{job}] = \text{"sailor"} \wedge t_2[\text{job}] = \text{"veteran"} \rightarrow t_1 \prec_{\text{job}} t_2)$ $\varphi_4: \forall t_1, t_2 (t_1[\text{kids}] < t_2[\text{kids}] \rightarrow t_1 \prec_{\text{kids}} t_2)$ $\varphi_5: \forall t_1, t_2 (t_1 \prec_{\text{status}} t_2 \rightarrow t_1 \prec_{\text{job}} t_2)$ $\varphi_6: \forall t_1, t_2 (t_1 \prec_{\text{status}} t_2 \rightarrow t_1 \prec_{\text{AC}} t_2)$ $\varphi_7: \forall t_1, t_2 (t_1 \prec_{\text{status}} t_2 \rightarrow t_1 \prec_{\text{zip}} t_2)$ $\varphi_8: \forall t_1, t_2 (t_1 \prec_{\text{city}} t_2 \wedge t_1 \prec_{\text{zip}} t_2 \rightarrow t_1 \prec_{\text{county}} t_2)$
<i>Constant CFDs:</i>	$\psi_1: (\text{AC} = 213 \rightarrow \text{city} = \text{LA});$ $\psi_2: (\text{AC} = 212 \rightarrow \text{city} = \text{NY});$

Fig. 3. Currency constraints and constant CFDs

identify the true values of entity Edith, as follows:

- from the currency constraints  $\varphi_1$  and  $\varphi_2$ , we can conclude that her latest status is *deceased*;
- similarly, by  $\varphi_4$ , we find that her true kids value is 3 (assuming  $\text{null} < k$  for any number  $k$ );
- from (a) above and  $\varphi_5$ – $\varphi_7$ , we know that her latest job, AC and zip are *n/a*, 213 and 90058, respectively;
- after currency inferences (a) and (c), we can apply the CFD  $\psi_1$  and find her latest city as *LA*; and
- after the consistency inference (d), from (c) and (d) we get her latest county as *Vermont*, by applying  $\varphi_8$ .

Now we have identified a single tuple  $t_1 = (\text{Edith Shain, deceased, n/a, 3, LA, 213, 90085, Vermont})$  as the true values of Edith in  $E_1$  (the address is for her cemetery).  $\square$

This example suggests the following. (1) Data currency and consistency should be interleaved when resolving conflicts. Indeed, not only deducing currency orders helps us *improve the consistency* (e.g., from steps (a), (c) to (d)), but data consistency inferences also help us *identify the most current values* (e.g., step (e) is doable only after (d)). (2) Both data currency and consistency can be specified with constraints, and hence, can be processed in a uniform logical framework.

While the need for deducing the consistent and most current values has been advocated for conflict resolution [10], [22], prior work typically assumes the availability of timestamps. Previous work on data quality focuses on either data consistency (e.g., [1], [7], [13], [26]) or data currency (e.g., [15]). However, no models or algorithms are yet in place to combine data consistency and currency for *conflict resolution*.

**Contributions.** We propose to study conflict resolution by inferring *both* data currency *and* data consistency.

(1) We propose a model for conflict resolution (Section II). We specify data currency in terms of (a) *partial currency orders* denoting available (yet possibly incomplete) temporal information on the data, and (b) simple *currency constraints*, to express currency relationships derived from the semantics of the data. Data consistency is specified in terms of *constant CFDs* [13] on the latest values of the data. Given such a specification  $S_e$  on a set  $E$  of tuples pertaining to the same entity  $e$ , we aim to derive the true values of  $e$  from  $S_e$ .

(2) We introduce a framework for conflict resolution (Section III). One may find *some* true values of an entity from a

specification of an entity, but *not all*, as illustrated below.

**Example 3:** Consider the set  $E_2$  of tuples for entity George Mendonça (Fig. 2). Along the same lines as Example 2, we find that its true (name, kids) values are (*George Mendonça*, 2). However, we do not have sufficient information to infer the true values of the other attributes.  $\square$

In light of this, our framework *automatically derives* as many true values as possible from a given specification  $S_e$  of an entity  $e$ , identifies attributes for which the true values of  $e$  are not derivable from  $S_e$ , and *interacts* with users to solicit additional input for those attributes, so that all the true values of  $e$  can be derived from  $S_e$  and users’ input.

(3) We study problems fundamental to conflict resolution (Section IV). Given a specification  $S_e$ , we determine whether partial currency orders, currency constraints and CFDs in  $S_e$  have conflicts among themselves? Whether some other currency orders are implied by  $S_e$ ? Whether true values of an entity can be derived from  $S_e$ ? If not, what additional minimum currency information has to be provided so that the true values are derivable? We establish their complexity bounds, ranging from NP-complete and coNP-complete to  $\Sigma_2^P$ -complete. These results reveal the complexity *inherent to* conflict resolution.

(4) We develop several practical algorithms (Section V). We propose methods for finding (a) whether a specification  $S_e$  has conflicts, (b) what true values can be derived from  $S_e$ , and (c) a minimum set of attributes that require users’ input to find their true values. All these problems are *intractable*; in particular, the last problem is  $\Sigma_2^P$ -complete. Nevertheless, we provide efficient heuristic algorithms, by integrating inferences of data consistency and currency into a single process.

(5) We evaluate the accuracy and efficiency of our method using real-life and synthetic data (Section VI). We find that *unifying* currency and consistency *substantially improves* the accuracy of traditional methods, by 201% (F-measure).

We contend that this work provides fundamental results for conflict resolution, and proposes a practical solution via data currency and consistency in the *absence* of timestamps.

**Related work.** Conflict resolution has been studied for decades, started from [8]. It aims to combine data from different sources into a single representation (see [4], [10] for surveys). In that context, inconsistencies are typically resolved by selecting the max, min, avg, any value [4]. While the need

for current values was also observed there [10], [22], they are identified only by using *timestamps*. This work differs from the traditional work in the following. (1) We revise the conflict resolution problem to identify values of entities that are both *consistent* and most *current*. (2) We *do not* assume the availability of timestamps, which are often missing in practice [28]. (3) We resolve conflicts by using currency constraints and CFDs [1], [7], [13], instead of picking max, min, avg or any value. (4) We employ *automated reasoning* to identify true values by unifying the inferences of currency and consistency.

There has been work on truth discovery from data sources [9], [18], [27]. Their approaches include (1) vote counting and probabilistic computation based on the trustworthiness of data sources [18], [27]; (2) source dependencies to find copy relationships and reliable sources [9]; and (3) employing lineage information and probabilities [25]. In contrast, we assume no information about the accuracy of data sources, but derive true values based on data currency and consistency. In addition, we adopt a logical approach via automated reasoning about constraints, as opposed to probabilistic computation. This work is complementary to the previous work.

This work extends [13], [15]. A data currency model was presented in [15] with partial currency orders and denial constraints [1]. CFDs were studied for specifying data consistency [13]. This work differs from [13], [15] in the following. (1) We propose a conflict resolution model that combines data currency and consistency. In contrast, [15] only studies data currency, while [13] only considers data consistency. (2) We *interleave* inferences of data currency and consistency, which is far more intriguing than handling currency and consistency separately, and requires new techniques to capture the interaction between the two. (3) We use currency constraints, which are simpler than denial constraints, to strike a balance between the complexity of inferring true values and the expressivity needed for specifying currency (Section IV). (4) *No practical algorithms* were given in [15] for deriving current values.

Previous work on data consistency [1], [7], [13], [20], [26] has been focusing on consistent query answering and data repairing [2], topics different from conflict resolution. The study of preferred repairs [20] also advocates partial orders. It differs from the currency orders we study here in that they use PTIME functions to rank different repairs over the entire database, whereas we derive the currency orders by *automated reasoning about both* available partial temporal information and currency constraints. Preferred repairs are implemented by [7] via a cost metric, and by [26] based on a decision theory, which can be incorporated into our framework.

There has also been a large body of work on temporal databases (see [6] for a survey). In contrast to that line of work, we do not assume the availability of timestamps.

It has recently been shown that temporal information helps record linkage identify records that refer to the same entity [21]. Here we show that data currency also helps conflict resolution, a different process that takes place *after* record linkage has identified tuples pertaining to the same entity. While [21] is based on timestamps, we do not assume it here.

## II. A CONFLICT RESOLUTION MODEL

We now introduce our conflict resolution model. We start with currency (Section II-A) and consistency (Section II-B) specifications. We then present the model (Section II-C).

### A. Data Currency

We specify the currency of data by means of (a) partial currency orders, and (b) currency constraints.

**Data with partial currency orders.** Consider a relation schema  $R = (A_1, \dots, A_n)$ , where each attribute  $A_i$  has a domain  $\text{dom}(A_i)$ . In this work we focus on *entity instances*  $I_e$  of  $R$ , which are sets of tuples of  $R$  all pertaining to the *same* real-world entity  $e$ , and are typically much smaller than a database instance. Such entity instances can be identified by *e.g.*, record linkage techniques (see [12] for a survey).

For an attribute  $A_i \in R$  and an entity instance  $I_e$  of  $R$ , we denote by  $\text{adom}(I_e.A_i)$  the set of  $A_i$ -attribute values that occur in  $I_e$ , referred to as *the active domain of  $A_i$  in  $I_e$* .

For example, two entity instances are given in Fig. 2:  $E_1 = \{r_1, r_2, r_3\}$  for entity “Edith”, and  $E_2 = \{r_4, r_5, r_6\}$  for “George”; and  $\text{adom}(E_1.\text{city}) = \{\text{NY}, \text{SFC}, \text{LA}\}$ .

A *temporal instance*  $I_t$  of  $I_e$  is given as  $(I_e, \preceq_{A_1}, \dots, \preceq_{A_n})$ , where each  $\preceq_{A_i}$  is a partial order on  $I_e$ , referred to as *the currency order for attribute  $A_i$*  for the entity represented by  $I_e$ . For  $t_1, t_2 \in I_e$ ,  $t_1 \preceq_{A_i} t_2$  if and only if (iff) either  $t_1$  and  $t_2$  share the same  $A_i$ -attribute value (*i.e.*,  $t_1[A_i] = t_2[A_i]$ ), or that  $t_2[A_i]$  is more current than  $t_1[A_i]$  (denoted by  $t_1 \prec_{A_i} t_2$ ).

Intuitively, currency orders represent *available* temporal information about the data. Observe that  $\preceq_{A_i}$  is a *partial order*, possibly empty. For example, for  $E_1$  above, we only know that  $r_3 \preceq_{\text{kids}} r_1$  and  $r_3 \preceq_{\text{kids}} r_2$  since  $r_3[\text{kids}]$  is null, which are in the currency order  $\preceq_{\text{kids}}$ , while the currency orders for other attributes are empty, excluding the case when tuples carry the same attribute value. Similarly for  $E_2$ . In particular,  $t_1 \preceq_{A_i} t_2$  if  $t_1[A_i]$  is null, *i.e.*, an attribute with value missing is ranked the lowest in the currency order.

**Current instances.** Currency orders are often incomplete. Hence we consider possible completions of currency orders.

A *completion*  $I_t^c$  of  $I_t$  is a temporal instance  $I_t^c = (I_e, \preceq_{A_1}^c, \dots, \preceq_{A_n}^c)$ , such that for each  $i \in [1, n]$ , (1)  $\preceq_{A_i} \subseteq \preceq_{A_i}^c$ , and (2) for all tuples  $t_1, t_2 \in I_e$ , either  $t_1 \preceq_{A_i}^c t_2$  or  $t_2 \preceq_{A_i}^c t_1$ . That is,  $\preceq_{A_i}^c$  induces a *total order* on tuples in  $I_e$ .

That is,  $I_t^c$  totally sorts the attribute values in  $I_e$  such that the most current value of each attribute is the last in the order.

We define *the most current  $A_i$ -attribute value of  $I_t^c$*  to be  $t[A_i]$  that comes last in the total order  $\preceq_{A_i}^c$ . The *current tuple* of  $I_t^c$ , denoted by  $\text{LST}(I_t^c)$  (*i.e.*, last), is the tuple  $t_l$  such that for each attribute  $A_i$ ,  $t_l[A_i]$  is the most current  $A_i$ -value of  $I_t^c$ , *i.e.*,  $t_l$  contains the most current values from  $I_t^c$ .

**Currency constraints.** One can derive additional currency information from the semantics of the data, which is modeled as *currency constraints*. A currency constraint  $\varphi$  is of the form

$$\forall t_1, t_2 (\omega \rightarrow t_1 \prec_{A_i} t_2),$$

where  $\omega$  is a conjunction of predicates of the form: (1)  $t_1 \prec_{A_i} t_2$ , *i.e.*,  $t_2$  is more current than  $t_1$  in attribute  $A_i$ ; (2)

$t_1[A_i]$  op  $t_2[A_i]$ , where op is one of  $=, \neq, >, <, \leq, \geq$ ; and (3)  $t_i[A_i]$  op  $c$  for  $i \in \{1, 2\}$ , where  $c$  is a constant.

In contrast to denial constraints in the model of [15], currency constraints are defined on two tuples, like functional dependencies. Such constraints suffice to specify currency information commonly found in practice (see, e.g., Example 2).

Currency constraints are interpreted over completions  $I_t^c$  of  $I_t$ . We say that  $I_t^c$  satisfies  $\varphi$ , denoted by  $I_t^c \models \varphi$ , if for any two tuples  $t_1, t_2$  in  $I_e$ , if these tuples and related order information in  $I_t^c$  satisfy the predicates in  $\omega$ , following the standard semantics of first-order logic, then  $t_1 \prec_{A_r}^c t_2$ .

We say that  $I_t^c$  satisfies a set  $\Sigma$  of currency constraints, denoted by  $I_t^c \models \Sigma$ , if  $I_t^c \models \varphi$  for all  $\varphi \in \Sigma$ .

**Example 4:** Recall the entity instances  $E_1$  and  $E_2$  given in Fig. 2. Currency constraints on these instances include  $\varphi_{1-4}$  as specified in Fig. 3 and interpreted in Example 2.

It is readily verified that for any completion  $E_1^c$  of  $E_1$ , if it satisfies these constraints, it yields  $\text{LST}(E_1^c)$  of the form  $(\text{Edith}, \text{deceased}, n/a, 3, x_{\text{city}}, 213, 90058, x_{\text{county}})$  for Edith, in which the most current values for attributes name, status, job, kids, AC and zip are deduced from the constraints and remain unchanged, while  $x_{\text{city}}$  and  $x_{\text{county}}$  are values determined by the total currency order given in  $E_1^c$ . Observe that the values of the current tuple are taken from *different tuples* in  $E_1$ , e.g., kids = 3 from  $r_2$  and AC = 213 from  $r_3$ .

Similarly, for any completion of  $E_2$ , its current tuple has the form  $(\text{George}, x_{\text{status}}, x_{\text{job}}, 2, x_{\text{city}}, x_{\text{AC}}, x_{\text{zip}}, x_{\text{county}})$ , if they satisfy all constraints. Hence, currency constraints help us find some but not *all* of the most current values of entities.  $\square$

### B. Data Consistency

To specify the consistency of data, we use a simple class of conditional functional dependencies (CFDs) [13] as follows.

A *constant* CFD [13]  $\psi$  on a relation schema  $R$  is of the form  $t_p[X] \rightarrow t_p[B]$ , where (1)  $X \subseteq R, B \in R$ ; and (2)  $t_p$  is the *pattern tuple* of  $\psi$  with attributes in  $X$  and  $B$ , where for each  $A$  in  $X \cup \{B\}$ ,  $t_p[A]$  is a *constant* in  $\text{dom}(A)$  of  $A$ .

For example,  $\psi_1$  and  $\psi_2$  in Table 3 are constant CFDs on the relation of Table 2, as interpreted in Example 2.

Such CFDs are defined on *the current tuple* of a completion. Consider a completion  $I_t^c$  of  $I_t$  and let  $t_l = \text{LST}(I_t^c)$  be the current tuple of  $I_t^c$ . We say that the completion  $I_t^c$  satisfies a constant CFD  $\psi = t_p[X] \rightarrow t_p[B]$ , denoted by  $I_t^c \models \psi$ , iff when  $t_l[X] = t_p[X]$  then  $t_l[B] = t_p[B]$ .

Intuitively, this assures that if  $t_l[X] = t_p[X]$  and if  $t_l[X]$  contains the most current  $X$ -attribute values, then  $t_l[B]$  can be *repaired* by taking the value  $t_p[B]$  in the pattern, and moreover,  $t_l[B]$  is the most current value in attribute  $B$ .

We say that  $I_t^c$  satisfies a set  $\Gamma$  of constant CFDs, denoted as  $I_t^c \models \Gamma$ , iff  $I_t^c \models \psi$  for each  $\psi \in \Gamma$ .

Observe that a constant CFD is defined on a *single tuple*  $\text{LST}(I_t^c)$ . In light of this, we do not need general CFDs of [13] here, which are typically defined on *two tuples*.

**Example 5:** Recall the current tuples for  $E_1$  in Example 4. Then all completions of  $E_1$  that satisfy  $\psi_1$  in Fig. 3 have

the form  $(\text{Edith}, \text{deceased}, n/a, 3, \text{LA}, 213, 90058, \text{Vermont})$ , in which  $x_{\text{city}}$  is instantiated as  $\text{LA}$  by  $\psi_1$ , and as a result,  $x_{\text{county}}$  becomes  $\text{Vermont}$  by the currency constraint  $\varphi_8$ .  $\square$

### C. Conflict Resolution

We are ready to bring currency and consistency together.

**Specifications.** A *specification*  $S_e = (I_t, \Sigma, \Gamma)$  of an entity consists of (1) a temporal instance  $I_t = (I_e, \preceq_{A_1}, \dots, \preceq_{A_n})$ ; (2) a set  $\Sigma$  of currency constraints; and (3) a set  $\Gamma$  of constant CFDs. A completion  $I_t^c = (I_e, \preceq_{A_1}^c, \dots, \preceq_{A_n}^c)$  of  $I_t$  is a *valid completion* of  $S_e$  if  $I_t^c$  satisfies both  $\Sigma$  and  $\Gamma$ . We say that  $S_e$  is *valid* if there exists a valid completion  $I_t^c$  of  $S_e$ , e.g., the specification of  $E_1$  (or  $E_2$ ) and the constraints in Fig. 3 is valid.

**True values.** There may be many valid completions  $I_t^c$ , each leading to a possibly different current tuple  $\text{LST}(I_t^c)$ . When two current tuples differ in some attribute, there is a *conflict*. We aim to resolve such conflicts. If all such current tuples agree on *all* attributes, then the specification is conflict-free, and a *unique* current tuple exists for the entity  $e$  specified by  $S_e$ . In this case, we say that this tuple is the true value of  $e$ .

More formally, the *true value* of  $S_e$ , denoted by  $\text{T}(S_e)$ , is the *single tuple*  $t_c$  such that for *all valid* completions  $I^c$  of  $S_e$ ,  $t_c = \text{LST}(S_e)$ , if it exists. For each attribute  $A_i$  of  $R$ , we call  $t_c[A_i]$  the *true value* of  $A_i$  in  $S_e$ .

**The conflict resolution problem.** Consider a specification  $S_e = (I_t, \Sigma, \Gamma)$ , where  $I_t = (I_e, \preceq_{A_1}, \dots, \preceq_{A_n})$ . Given  $S_e$ , conflict resolution is to find the minimum amount of additional currency information such that the true value exists.

The additional currency information is specified in terms of a *partial temporal order*  $O_t = (I, \preceq'_{A_1}, \dots, \preceq'_{A_n})$ . We use  $S_e \oplus O_t$  to denote the extension  $S'_e = (I', \Sigma, \Gamma)$  of  $S_e$  by enriching  $I_t$  with  $O_t$ , where  $I' = (I_e \cup I, \preceq_{A_1} \cup \preceq'_{A_1}, \dots, \preceq_{A_n} \cup \preceq'_{A_n})$ . We only consider partial temporal orders  $O_t$  such that  $\preceq_{A_i} \cup \preceq'_{A_i}$  is a partial order for all  $i \in [1, n]$ .

We use  $|O_t|$  to denote  $\sum_{i \in [1, n]} |\preceq'_{A_i}|$ , i.e., the sum of the sizes of all the partial orders in  $O_t$ .

Given a valid specification  $S_e = (I_t, \Sigma, \Gamma)$  of an entity, the *conflict resolution problem* is to find a partial temporal order  $O_t$  such that (a)  $\text{T}(S_e \oplus O_t)$  exists and (b)  $|O_t|$  is minimum.

**Example 6:** Recall from Example 4 the current tuples for George. Except for name and kids, we do not have a unique current value for the other attributes. Nonetheless, if a partial temporal order  $O_t$  with, e.g.,  $r_6 \prec_{\text{status}} r_5$  is provided by the users (i.e., status changes from *unemployed* to *retired*), then the true value of George in  $E_2$  can be derived as  $(\text{George}, \text{retired}, \text{veteran}, 2, \text{NY}, 212, 12404, \text{Accord})$  from the currency constraints and CFDs of Fig. 3.  $\square$

## III. A CONFLICT RESOLUTION FRAMEWORK

We propose a framework for conflict resolution. As depicted in Fig. 4, given a specification  $S_e = (I_t, \Sigma, \Gamma)$  of an entity  $e$ , the framework is to find the true value  $\text{T}(S_e)$  of  $e$  by reasoning about data currency and consistency, and by interacting with the users to solicit additional data currency information.

The framework provides the users with suggestions. A *suggestion* is a minimum set  $\mathcal{A}$  of attributes of  $e$  such that

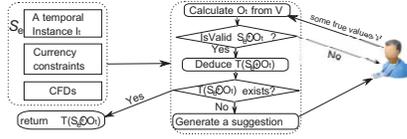


Fig. 4. Framework overview

if the true values of these attributes are provided by the users,  $T(S_e)$  is automatically deduced from the users' input,  $\Sigma$ ,  $\Gamma$  and  $I_t$ . The true values for  $\mathcal{A}$  are represented as a temporal order  $O_t$ . More specifically, the framework works as follows.

(1) *Validity checking*. It first inspects whether  $S_e \oplus O_t$  is valid, via automated reasoning, where  $O_t$  is a partial temporal order provided by the users (see step (4) below), *initially empty*. If so, it follows the 'Yes' branch. Otherwise the users need to revise  $O_t$  by following the 'No' branch.

(2) *True value deducing*. After  $S_e \oplus O_t$  is validated, it derives as many true values as possible, via automated reasoning.

(3) *Finding the true value*. If  $T(S_e \oplus O_t)$  exists, it terminates and returns the true value, by following the 'Yes' branch. Otherwise, it follows the 'No' branch and goes to step (4).

(4) *Generating suggestions*. It computes a suggestion  $\mathcal{A}$  along with its candidate values from the active domain of  $S_e$ , such that if the users pick and validate the true values for  $\mathcal{A}$ , then  $T(S_e \oplus O_t)$  is warranted to be found. The users are expected to provide  $V$ , the true values of *some attributes* in  $\mathcal{A}$ , represented as a partial temporal order  $O_t$ . Given  $O_t$ ,  $S_e \oplus O_t$  is constructed and the process goes back to step (1).

The process proceeds until  $T(S_e \oplus O_t)$  is found, or when the users opt to settle with true values for a subset of attributes of  $e$ . That is, if users do not have sufficient knowledge about the entity, they may let the system derive true values for as many attributes as possible, and revert to the traditional methods to pick the max, min, avg, any values for the rest of the attributes.

**Remarks.** (1) To specify users' input, let  $I_t$  in  $S_e$  be  $(I_e, \preceq_{A_1}, \dots, \preceq_{A_n})$  and  $\mathcal{A} \cup \mathcal{A}' \cup \mathcal{B} = \{A_1, \dots, A_n\}$ , where (i)  $\mathcal{A}$  is the set of attributes identified in step (4) for which the true values are unknown; (ii) for  $\mathcal{B}$ , their true values  $V_{\mathcal{B}}$  have been deduced (step (2)); and (iii)  $\mathcal{A}'$  is the set of attributes whose true values can be deduced from  $V_{\mathcal{B}}$  and the suggestion for  $\mathcal{A}$ . Given a suggestion, the user is expected to provide a set  $V$  of true values for (a subset of)  $\mathcal{A}$ . Here  $V$  consists of either the candidate values from the suggestion, or some *new* values not in the active domains of  $S_e$  that users opt to choose. The users *do not* have to enter values for *all* attributes in  $\mathcal{A}$ .

From the input  $V$ , a partial temporal order  $O_t$  is automatically derived, by treating  $V$  as the most current values of those attributes involved. Indeed,  $O_t$  has the form  $(I_e \cup \{t_o\}, \preceq'_{A_1}, \dots, \preceq'_{A_n})$ , where  $t_o$  is a new tuple such that for all attributes  $A$ ,  $t_o[A] = V(A)$  if  $V$  has a value  $V(A)$  for  $A$ , and  $t_o[A] = \text{null}$  otherwise, while  $t_o[\mathcal{B}] = V_{\mathcal{B}}$  remains unchanged. Moreover,  $\preceq'_A$  extends  $\preceq_A$  by including  $t[A] \preceq_A t_o[A]$  if  $t_o[A] \neq \text{null}$ , for all tuples  $t \in I_e$ . Then  $S_e \oplus O_t$  can be readily defined.

(2) There have been efficient methods for discovering constant CFDs, e.g., [14]. Along the same lines as CFD discovery [5], [14], automated methods can be developed for discovering

currency constraints from (possibly dirty) data. With certain quality metric in place [5], the constraints discovered can be as accurate as those manually designed (such as those given in Fig. 3), and can be used by the framework as input.

(3) To simplify the discussion we do not allow users to change constraints in  $S_e$ . We defer this issue to Section VII.

(4) We assume the values from entities were once correct. When an entity contains errors, we may work on different samples and only take those orders that are either consistent among the samples, or with sufficient support (e.g., frequency).

#### IV. FUNDAMENTAL PROBLEMS

We next identify fundamental problems associated with conflict resolution based on both data currency and consistency, and establish their complexity. These results are not only of theoretical interest, but also tell us where the complexity arises, and hence guide us to develop effective (heuristic) algorithms. All proofs of the results are in the full version [17].

**Satisfiability.** The *satisfiability problem* is to determine, given a specification  $S_e = (I_t, \Sigma, \Gamma)$  of an entity, whether  $S_e$  is *valid*, i.e., whether there exists a valid completion of  $S_e$ .

It is to check whether  $S_e$  makes sense, i.e., whether the currency constraints, CFDs and partial orders in  $S_e$ , when put together, have conflicts themselves. The analysis is needed by the step (1) of the framework of Fig. 4, among other things.

The problem is important, but is NP-complete. One might think that the absence of currency constraints or CFDs would simplify the analysis. Unfortunately, its intractability is *robust*.

**Theorem 1:** *The satisfiability problem for entity specifications is NP-complete. It remains NP-hard for valid specifications  $S_e = (I_t, \Sigma, \Gamma)$  of an entity when (1) both  $\Sigma$  and  $\Gamma$  are fixed; (2)  $\Gamma = \emptyset$ , i.e., with only currency constraints; or (3)  $\Sigma = \emptyset$ , i.e., when only constant CFDs are present.*

**Implication.** Consider a valid specification  $S_e = (I_t, \Sigma, \Gamma)$  of an entity and a partial temporal order  $O_t = (I_e, \preceq'_{A_1}, \dots, \preceq'_{A_n})$ . We say that  $O_t$  is *implied* by  $S_e$ , denoted by  $S_e \models O_t$ , iff for all valid completions  $I_t^c$  of  $S_e$ ,  $O_t \subseteq I_t^c$ . Here  $O_t \subseteq I_t^c$  if  $\preceq'_{A_i} \subseteq \preceq_{A_i}^c$  for all  $i \in [1, n]$ , where  $I_t^c = (I_e, \preceq_{A_1}^c, \dots, \preceq_{A_n}^c)$ .

The *implication problem* is to decide, given a valid specification  $S_e$  and a partial temporal order  $O_t$ , whether  $S_e \models O_t$ .

That is, no matter how we complete the temporal instance  $I_t$  of  $S_e$ , as long as the completion is valid, it includes  $O_t$ . The implication analysis is conducted at step (2) of the framework of Fig. 4, for deducing true values of attributes.

Unfortunately, the implication problem is coNP-complete.

**Theorem 2:** *The implication problem for conflict resolution is coNP-complete.*

**True value deduction.** The *true value problem* is to decide, given a valid specification  $S_e$  for an entity, whether  $T(S_e)$  exists. That is, there exists a tuple  $t_c$  such that for all valid completions  $I_t^c$  of  $S_e$ ,  $\text{LST}(I_t^c) = t_c$ .

This analysis is needed by step (3) of the framework (Fig. 4) to decide whether  $S_e$  has enough information to deduce  $T(S_e)$ .

However, this problem is also nontrivial: it is intractable.

**Theorem 3:** *The true value problem for conflict resolution is coNP-complete.*

**Coverage analysis.** The *minimum coverage problem* is to determine, given a valid specification  $S_e = (I_t, \Sigma, \Gamma)$  and a positive integer  $k$ , whether there exists a partial temporal order  $O_t$  such that (1)  $\top(S_e \oplus O_t)$  exists, and (2)  $|O_t| \leq k$ .

Intuitively, this is to check whether one can add a partial temporal order  $O_t$  of a *bounded* size to a specification such that the enriched specification has sufficient information to deduce all the true values of an entity. The analysis of *minimum*  $O_t$  is required by step (4) of the framework of Fig. 4.

This problem is, unfortunately,  $\Sigma_2^P$ -complete (NP<sup>NP</sup>).

**Theorem 4:** *The minimum coverage problem is  $\Sigma_2^P$ -complete.*

**Remark.** From the results we find the following.

(1) The main conclusion is that these problems are hard. In fact as we have shown in [17], all the lower bounds remain intact for valid specifications  $S_e = (I_t, \Sigma, \Gamma)$  of an entity when (1) both  $\Sigma$  and  $\Gamma$  are fixed; (2)  $\Gamma = \emptyset$ , *i.e.*, when constant CFDs are absent; or (3)  $\Sigma = \emptyset$ , *i.e.*, when currency constraints are absent. Hence unless P = NP, efficient algorithms for solving these problems are necessarily *heuristic*.

(2) The results not only reveal the complexity of conflict resolution, but also advance our understanding of data currency and consistency. Indeed, while the minimum coverage problem is particular for conflict resolution and has *not* been studied before, the other problems are also of interest to the study of data currency. Theorems 1, 2 and 3 show that currency constraints make our lives easier as opposed to denial constraints: they reduce the complexity of inferring data currency reported in [15], from  $\Sigma_2^P$ -complete,  $\Pi_2^P$ -complete (coNP<sup>NP</sup>) and  $\Pi_2^P$ -complete down to NP-complete, coNP-complete and coNP-complete, respectively. When it comes to data consistency, it is known that the satisfiability and implication problems for general CFDs are NP-complete and coNP-complete, respectively [13]. Theorems 1 and 2 give a *stronger* result: these lower bounds already hold for constant CFDs.

## V. ALGORITHMS FOR CONFLICT RESOLUTION

We next provide algorithms underlying the framework depicted in Fig. 4. We first present an algorithm for checking whether a specification is valid (step (1) of the framework; Section V-A). We then study how to deduce true attribute values from a valid specification (step (2); Section V-B). Finally, we show how to generate suggestions (step (4); Section V-C).

### A. Validity Checking

We start with algorithm *IsValid* that, given a specification  $S_e = (I_t, \Sigma, \Gamma)$ , returns true if  $S_e$  is valid, and false otherwise. As depicted in Fig. 4, *IsValid* is invoked for an initial specification  $S_e$  and its extensions  $S_e \oplus O_t$  with users' input.

Theorem 1 tells us that it is NP-complete to determine whether  $S_e$  is valid. Hence *IsValid* is necessarily heuristic if it is to be efficient. We approach this by reducing the problem to SAT, one of the most studied NP-complete problem, which is to decide whether a Boolean formula is satisfiable

(see, e.g., [3]). Several high-performance tools for SAT (SAT-solvers) are already in place [3], which have proved effective in software verification, AI and operations research, among others. For instance, MiniSAT [19] can effectively solve a formula with 4,500 variables and 100K clauses in 1 second.

**Algorithm.** Using a SAT-solver, We outline *IsValid* as follows. (1) *Instantiation*( $S_e$ ): It expresses  $S_e$  as a set  $\Omega(S_e)$  of predicate formulas. (2) *ConvertToCNF*( $\Omega(S_e)$ ): It then converts  $\Omega(S_e)$  into a CNF  $\Phi(S_e)$  (the conjunctive normal form) such that  $S_e$  is valid iff  $\Phi(S_e)$  satisfiable. (3) Finally, it applies an SAT-solver to  $\Phi(S_e)$ , and returns true iff  $\Phi(S_e)$  is true.

We next present the details of procedures *Instantiation* and *ConvertToCNF*. We denote also by  $R$  the set  $\{A_i \mid i \in [1, n]\}$  of attributes of  $R$ . We define a strict partial order  $\prec_{A_i}^v$  on the values in the union of  $\text{adom}(I_e.A_i)$  and all the constants that appear in attribute  $A_i$  of some constant CFDs in  $\Gamma$ .

**Instantiation.** We express the currency orders, currency constraints and CFDs of  $S_e$  in a uniform set  $\Omega(S_e)$  of constraints, referred to as *instance constraints*. This is done by instantiating variables in  $S_e$  with data in active domains as follows.

(1) *Currency orders.* To encode currency orders in  $I_t$ , for each  $A_i \in R$ , we include the following constraints in  $\Omega(S_e)$ .

- (a) Partial orders in  $I_t$ : ( $\text{true} \rightarrow t_1[A_i] \prec_{A_i}^v t_2[A_i]$ ) for each  $t_1 \preceq_{A_i} t_2$  in  $I_t$ , as long as  $t_1[A_i] \neq t_2[A_i]$ .
  - (b) Transitivity of  $\prec_{A_i}$ : ( $a_1 \prec_{A_i}^v a_2 \wedge a_2 \prec_{A_i}^v a_3 \rightarrow a_1 \prec_{A_i}^v a_3$ ) for all distinct values  $a_1, a_2, a_3$  in  $\text{adom}(I_e.A_i)$ .
  - (c) Asymmetry: ( $a \prec_{A_i}^v b \rightarrow \neg(b \prec_{A_i}^v a)$ ) for  $a, b \in \text{adom}(I_e.A_i)$ .
- Intuitively, these assure that each  $\prec_{A_i}$  is a *strict partial order* (via (b) and (c)), and express available temporal information in  $I_t$  as predicate formulas (via (a)).

(2) *Currency constraints.* For each currency constraint  $\varphi = \forall t_1, t_2 (\omega \rightarrow t_1 \prec_{A_r} t_2)$  in  $\Sigma$  and for all distinct tuples  $s_1, s_2 \in I_e$ , we include the following constraint in  $\Omega(S_e)$ :

$$\text{ins}(\omega, s_1, s_2) \rightarrow s_1[A_r] \prec_{A_r}^v s_2[A_r],$$

where  $\text{ins}(\omega, s_1, s_2)$  is obtained from  $\omega$  by (a) substituting  $s_i[A_j]$  for  $t_i$  and  $\prec_{A_j}^v$  for  $\prec_{A_j}$  in each predicate  $t_1 \prec_{A_j} t_2$ , for  $i \in [1, 2]$ ; and (b) evaluating each conjunct of  $\omega$  defined with a comparison operator to its truth value *w.r.t.*  $s_1$  and  $s_2$ . Intuitively,  $\text{ins}(\omega, s_1, s_2)$  “instantiates”  $\omega$  with  $s_1$  and  $s_2$ .

**Example 7:** For currency constraint  $\varphi_1$  in Fig. 3, and tuples  $r_1$  and  $r_2$  in Fig. 2 for Edith, its instance constraint is ( $\text{true} \rightarrow \text{working} \prec_{\text{status}}^v \text{retired}$ ). Note that the precondition of  $\varphi_1$  is evaluated true on these two particular tuples.

For  $\varphi_6$  and  $r_1, r_2$ , we get ( $\text{working} \prec_{\text{status}}^v \text{retired} \rightarrow 212 \prec_{AC}^v 415$ ), by replacing  $\prec_{\text{status}}$  with  $\prec_{\text{status}}^v$ , and by replacing tuples with their corresponding attribute values.  $\square$

(3) *Constant CFDs.* For each constant CFD  $t_p[X] \rightarrow t_p[B]$  in  $\Gamma$  and each  $b \in \text{adom}(I_e.B) \setminus \{t_p[B]\}$ ,  $\Omega(S_e)$  includes

$$\psi = (\omega_X \rightarrow b \prec_B^v t_p[B]),$$

where  $\omega_X$  is a conjunction of all formulas of the form  $a \prec_{A_j}^v t_p[A_j]$  for each  $a \in \text{adom}(I_e.A_j) \setminus \{t_p[A_j]\}$  and each  $A_j \in X$ .

Intuitively, constraint  $\psi$  asserts that if  $t_p[X]$  is true in attributes  $X$ , then  $t_p[B]$  is the true value of  $B$ .

**Example 8:** Recall constant CFD  $\psi_1$  (Fig. 3). For  $E_1$  (Edith), it is encoded by two instance constraints below, in  $\Omega_{E_1}$ :

$$\begin{aligned} 212 \prec_{AC}^v 213 \wedge 415 \prec_{AC}^v 213 \rightarrow NY \prec_{city}^v LA, \\ 212 \prec_{AC}^v 213 \wedge 415 \prec_{AC}^v 213 \rightarrow SFC \prec_{city}^v LA, \end{aligned}$$

*i.e.*,  $LA$  is her true city value if her true AC value is 213.  $\square$

**ConvertToCNF.** We convert  $\Omega(S_e)$  into a CNF  $\Phi(S_e)$  as follows. We substitute a Boolean variable  $x_{a_1 a_2}^{A_i}$  for each predicate  $a_1 \prec_{A_i}^v a_2$  in  $\Omega(S_e)$ , and write each formula of the form  $(x_1 \wedge \dots \wedge x_k \rightarrow x_{k+1})$  as  $(\neg x_1 \vee \dots \vee \neg x_k \vee x_{k+1})$ . Then  $\Phi(S_e)$  is a CNF with the conjunction of all formulas in  $\Omega(S_e)$ .

One can readily verify the following (by contradiction), which justifies the reduction from the validity of  $S_e$  to SAT.

**Lemma 5:** *Specification  $S_e$  is valid iff its converted CNF  $\Phi(S_e)$  is satisfiable.*

**Complexity:** Observe the following. (a) The size  $|\Omega(S_e)|$  of  $\Omega(S_e)$  is bounded by  $O((|\Sigma| + |\Gamma|)|I_t|^2 + |I_t|^3)$ , since encoding currency orders, currency constraints and constant CFDs is in time  $O(|I_t|^3)$ ,  $O(|\Sigma||I_t|^2)$  and  $O(|\Gamma||I_t|^2)$ , respectively. (b) It takes  $O(|\Omega(S_e)|)$  time to convert  $\Omega(S_e)$  into  $\Phi(S_e)$ . Hence the size of the CNF  $\Phi(S_e)$  is bounded by  $O((|\Sigma| + |\Gamma|)|I_t|^2 + |I_t|^3)$ . In practice, an entity instance  $I_t$  is typically *much smaller than* a database, and the sets  $\Sigma$  and  $\Gamma$  of constraints are also *small*. As will be seen in Section VI, SAT-solvers can efficiently process CNFs of this size.

### B. Deducing True Values

We now develop an algorithm that, given a valid specification  $S_e = (I_t, \Sigma, \Gamma)$  of an entity  $e$ , deduces *true values* for as many attributes of  $e$  as possible. It finds a maximum partial order  $O_d$  such that  $S_e \models O_d$ , *i.e.*, (a) for all valid completions  $I_t^c$  of  $S_e$ ,  $O_d \subseteq I_t^c$  (Section IV), and (b) for tuples  $t_1, t_2 \in I_e$  and  $A_i \in R$ , if  $S_e \models t_1 \prec_{A_i} t_2$  then  $t_1 \prec_{A_i} t_2$  is in  $O_d$ .

As an immediate corollary of Theorem 2, one can show that this problem is also coNP-complete, even when either  $\Sigma$  or  $\Gamma$  is fixed or absent. Thus we give a heuristics to strike a balance between its complexity and accuracy. The algorithm is based on the following lemma, which is easy to verify.

**Lemma 6:** *For CNF  $\Phi(S_e)$  converted from a valid specification  $S_e$ , and for tuples  $t_1, t_2$  in  $S_e$  with  $t_1[A_i] = a_1$  and  $t_2[A_i] = a_2$ ,  $S_e \models t_1 \prec_{A_i} t_2$  iff  $\Phi(S_e) \rightarrow x_{a_1 a_2}^{A_i}$  is a tautology, where  $x_{a_1 a_2}^{A_i}$  is the variable denoting  $a_1 \prec_{A_i}^v a_2$  in  $\Phi(S_e)$ .*

Here  $\Phi(S_e) \rightarrow x_{a_1 a_2}^{A_i}$  indicates that for any truth assignment  $\mu$ , if  $\mu$  satisfies  $\Phi(S_e)$ , then  $\mu(x_{a_1 a_2}^{A_i})$  is *true*, *i.e.*, the one-literal clause  $x_{a_1 a_2}^{A_i}$  is implied by  $\Phi(S_e)$ , which in turn encodes  $S_e$ . Based on this, our algorithm checks one-literal clauses in  $\Phi(S_e)$  one by one, and enriches  $O_d$  accordingly.

**Algorithm.** The algorithm, referred to as DeduceOrder, is given in Fig. 5. It first converts specification  $S_e$  to CNF  $\Phi(S_e)$  (line 1; see Section V-A). For each literal  $C$  of the form  $x_{a_1 a_2}^{A_i}$  or  $\neg x_{a_1 a_2}^{A_i}$ , it checks whether  $C$  is a clause in (implied by)  $\Phi(S_e)$  (line 3), and if so, adds it to  $O_d$  (lines 4-7). It then reduces  $\Phi(S_e)$  by using  $C$  and its negation  $\neg C$  (line 8). That is, for each clause  $C'$  that contains  $C$ , the entire  $C'$  is removed since  $C'$  is *true* if  $C$  has to be satisfied (*i.e.*, *true*). Similarly, for each clause  $C''$  that contains  $\neg C$ ,  $\neg C$  is removed from  $C''$ , as  $\neg C$  has to be *false*. The  $O_d$  is then returned (line 9).

---

### Algorithm DeduceOrder

---

*Input:* A valid specification  $S_e = (I_t, \Sigma, \Gamma)$  of an entity.

*Output:* A partial temporal order  $O_d$  such that  $S_e \models O_d$ .

1.  $\Omega(S_e) := \text{Instantiation}(S_e)$ ;  $\Phi(S_e) := \text{ConvertToCNF}(\Omega(S_e))$ ;
  2.  $O_d := (I_e, \emptyset, \dots, \emptyset)$ ;
  3. **while** there exists a one-literal clause  $C$  in  $\Phi(S_e)$  **do**  
*/\*  $x_{a_1 a_2}^{A_i}$  in  $C$  is the variable denoting  $a_1 \prec_{A_i}^v a_2$  \*/*
  4. **if**  $C$  is a one-literal clause  $(x_{a_1 a_2}^{A_i})$  **then**
  5.   add  $a_1 \prec_{A_i}^v a_2$  to  $O_d$ ;  $C_{\neg} := \neg x_{a_1 a_2}^{A_i}$ ;
  6. **if**  $C$  is a one-literal clause  $(\neg x_{a_1 a_2}^{A_i})$  **then**
  7.   add  $a_2 \prec_{A_i}^v a_1$  to  $O_d$ ;  $C_{\neg} := x_{a_1 a_2}^{A_i}$ ;
  8.   Reduce  $\Phi(S_e)$  by using  $C$  and  $C_{\neg}$ ; */\* see details below \*/*
  9. **return**  $O_d$ .
- 

Fig. 5. Algorithm DeduceOrder

**Example 9:** Consider  $E_2$  in Fig. 2 and the constraints of Fig. 3, DeduceOrder finds  $O_d$  including: (1)  $0 \prec_{kids}^v 2$  by  $\varphi_4$ , (2) *working*  $\prec_{status}^v$  *retired* by  $\varphi_1$ , (3) *sailor*  $\prec_{job}^v$  *veteran*,  $401 \prec_{AC}^v 212$  and  $02840 \prec_{zip}^v 12404$ , by (2) and  $\varphi_5$ ,  $\varphi_6$  and  $\varphi_7$ , respectively. A current tuple of George is then of the form  $(George, x_{status}, x_{job}, 2, x_{city}, x_{AC}, x_{zip}, x_{county})$ , with variables.

Assume that the users assure that the true value of the attribute status is *retired*. Then the algorithm can deduce the following from the extended specification:

- (a)  $x_{job}$ ,  $x_{AC}$  and  $x_{zip}$  as *n/a*, 212 and 12404, from tuple  $r_5$  via currency constraints  $\varphi_5$ ,  $\varphi_6$  and  $\varphi_7$ , respectively;
- (b)  $x_{city} = NY$ , from the true value of AC (*i.e.*, 212 deduced in step (a) above) and the constant CFD  $\psi_2$ ;
- (c)  $x_{county}$  as *Accord*, from constraint  $\varphi_8$  and the true values of city and zip deduced in steps (b) and (a), respectively.

The automated deduction tells us that the true value for George is  $t_2 = (George, \text{retired}, \text{n/a}, 2, NY, 212, 12404, \text{Accord})$ . This shows that *currency constraints* help *consistency* (from step (a) to (b)), and *vice versa* (*e.g.*, from (b) to (c)).  $\square$

**Complexity.** (1) It takes  $O((|\Sigma| + |\Gamma|)|I_t|^2 + |I_t|^3)$  time to convert  $S_e$  into  $\Phi(S_e)$  (line 1; see Section V-A). (2) The *total time* taken by the **while** loop (lines 3-8) is in  $O((|\Sigma| + |\Gamma|)|I_t|^2 + |I_t|^3)$ . Indeed, we maintain a hash-based index for literals  $C$ , in which the key is  $C$  and its value is the list of clauses in  $\Phi(S_e)$  that contain  $C$  or  $\neg C$ . In the process,  $\Phi(S_e)$  decreases monotonically. Hence in total it takes at most  $O(|\Phi(S_e)|)$  time to reduce  $\Phi(S_e)$  for *all literals*, where  $|\Phi(S_e)|$  is bounded by  $O((|\Sigma| + |\Gamma|)|I_t|^2 + |I_t|^3)$ . Taken together, the algorithm is in  $O((|\Sigma| + |\Gamma|)|I_t|^2 + |I_t|^3)$  time.

By Lemma 6, one might want to compute a temporal order  $O'_d$  consisting of all such variables  $x_{a_1 a_2}^{A_i}$  that  $\Phi(S_e) \wedge \neg x_{a_1 a_2}^{A_i}$  is *not* satisfiable. That is, for each variable  $x_{a_1 a_2}^{A_i}$ , we inspect  $\Phi(S_e) \wedge \neg x_{a_1 a_2}^{A_i}$  by invoking a SAT-solver. However, this approach, referred to as NaiveDeduce, calls the SAT-solver  $|I_t|^2$  times. As will be seen in Section VI, DeduceOrder finds  $O_d$  with its accuracy comparable to  $O'_d$ , without incurring the cost of repeatedly calling a SAT-solver.

**True value deduction.** Using  $O_d$  found by DeduceOrder, one can deduce true attributes values as follows: a value  $a_1$  is the true value of attribute  $A_i$  if for all values  $a_2 \in \text{adom}(I_e.A_i) \setminus \{a_1\}$ , the currency order  $a_2 \prec_{A_i}^v a_1$  is in  $O_d$ .

### C. Generating Suggestions

True value deduction given above finds us the true values  $V_B$  for a set of attributes  $B \subseteq R$ . To identify the true value of the entity  $e$  specified by  $S_e = (I_t, \Sigma, \Gamma)$ , we compute a suggestion for a set of attributes  $A \subseteq R$  such that if the true values for  $A$  are validated, the true value of *the entire*  $e$  can be determined, even for attributes in  $R \setminus (B \cup A)$  (see Fig. 4). Below we first define suggestions and a notion of derivation rules. We then provide an algorithm for computing suggestions.

#### C.1. Suggestions and Derivation rules

For an attribute  $A_i \in R \setminus B$ , we denote by  $V(A_i)$  the candidate true values for  $A_i$ , *i.e.*, for any  $a_1 \in V(A_i)$ , there exists no  $a_2 \in \text{adom}(I_e.A_i) \setminus \{a_1\}$  such that  $a_1 \prec_A^v a_2$  is in  $O_d$ . For a set  $X$  of attributes, we write  $V(X) = \{V(A_i) \mid A_i \in X\}$ .

**Suggestion.** A *suggestion* for  $S_e$  is a pair  $(\mathcal{A}, V(\mathcal{A}))$ , where  $\mathcal{A} = (A_1, \dots, A_m)$  is a set of attributes of  $R$  such that  $\mathcal{A} \cap B = \emptyset$  and (1) there exist values  $(a_1, \dots, a_m)$  such that if  $(a_1, \dots, a_m)$  are validated as the true values of  $\mathcal{A}$ , then the true value  $T(S_e)$  of  $S_e$  exists; and (2) for all possible values  $(a'_1, \dots, a'_m)$  that satisfy condition (1),  $a'_i$  is in  $V(A_i)$  for  $i \in [1, m]$ .

Intuitively, condition 1 says that when the true values of  $\mathcal{A}$  are validated, so is  $T(S_e)$ . That is, the true values of attributes in  $\mathcal{A}' = R \setminus (B \cup \mathcal{A})$  can be deduced from  $V_B$  and the true values of  $\mathcal{A}$ . Condition 2 says that  $V(\mathcal{A})$  gives “complete” candidates for the true values of  $\mathcal{A}$  in their active domains.

One naturally wants a suggestion to be as “small” as possible, so that it takes minimal efforts to validate the true values of  $\mathcal{A}$ . This motivates us to study the *minimum suggestion problem*, which is to find a suggestion  $(\mathcal{A}, V(\mathcal{A}))$  with the minimum number  $|\mathcal{A}|$  of attributes. Unfortunately, this problem is  $\Sigma_2^P$ -complete ( $\text{NP}^{\text{NP}}$ ), which can be verified by reduction from the minimum coverage problem (Theorem 4).

**Corollary 7:** *The minimum suggestion problem for conflict resolution is  $\Sigma_2^P$ -complete.*

In light of the high complexity, we develop an effective heuristics to compute suggestions. To do this, we examine how true values are inferred via currency constraints and CFDs, by expressing them as a uniform set of rules.

**Derivation rules.** A *true-value derivation rule* for  $S_e$  has the form  $(X, P[X]) \rightarrow (B, b)$ , where (1)  $X$  is a set of attributes,  $B$  is a single attribute, and (2)  $b$  is a value that is either in  $\text{adom}(I_e.B)$  or in attribute  $B$  of some constant CFD; and (3) for each  $A_i \in X$ ,  $P[A_i]$  is drawn from  $\text{adom}(I_e.A_i)$ . It assures if  $P[X]$  is the true value of  $X$ , then  $b$  is the true value of  $B$ .

Derivation rules are computed from instance constraints  $\Omega(S_e)$  of  $S_e$ , as shown below (to be elaborated shortly).

**Example 10:** Sample rules for George in Fig. 2 include:

- $n_1 : (\{\text{status}\}, \{\text{retired}\}) \rightarrow (\text{job}, \text{veteran})$
- $n_2 : (\{\text{status}\}, \{\text{retired}\}) \rightarrow (\text{AC}, 212)$
- $n_3 : (\{\text{status}\}, \{\text{retired}\}) \rightarrow (\text{zip}, 12404)$
- $n_4 : (\{\text{city}, \text{zip}\}, \{\text{NY}, 12404\}) \rightarrow (\text{county}, \text{Accord})$
- $n_5 : (\{\text{AC}\}, \{212\}) \rightarrow (\text{city}, \text{NY})$
- $n_6 : (\{\text{status}\}, \{\text{unemployed}\}) \rightarrow (\text{job}, \text{n/a})$
- $n_7 : (\{\text{status}\}, \{\text{unemployed}\}) \rightarrow (\text{AC}, 312)$

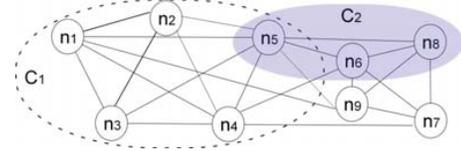


Fig. 6. Sample compatibility graph

- $n_8 : (\{\text{status}\}, \{\text{unemployed}\}) \rightarrow (\text{zip}, 60653)$
- $n_9 : (\{\text{city}, \text{zip}\}, \{\text{Chicago}, 60653\}) \rightarrow (\text{county}, \text{Bronzeville})$

Here rule  $n_5$  is derived from CFD  $\psi_2$ , which states that if his true AC is 212, then his true city must be NY. Rule  $n_1$  is from tuple  $r_5$  and constraint  $\varphi_5$  (Fig. 3), which states that if his true status is *retired*, then his true job is *veteran*. Note that in  $n_1$ , status is instantiated with *retired*. Similarly,  $n_6$  is derived from  $r_6$  and  $\varphi_5$ ;  $n_2$  and  $n_3$  (resp.  $n_7$  and  $n_8$ ) are derived from tuple  $r_5$  (resp.  $r_6$ ) and constraints  $\varphi_6$  and  $\varphi_7$ , respectively; and  $n_4$  (resp.  $n_9$ ) is derived from  $r_5$  (resp.  $r_6$ ) and  $\varphi_8$ .  $\square$

To find a suggestion, we want to find a set  $\mathcal{A}$  of attributes so that a maximum number of derivation rules can be applied to them at the same time, and hence, the true values of as many other attributes as possible can be derived from these rules. To capture this, we use the following notion.

**Compatibility graphs.** Consider a set  $\Pi$  of derivation rules. The *compatibility graph*  $G(N, E)$  of  $\Pi$  is an *undirected* graph, where (1) each node  $x$  in  $N$  is a rule  $(X_x, P_x[X_x]) \rightarrow (B_x, b_x)$  in  $\Pi$ , and (2) an edge  $(x, y)$  is in  $E$  iff  $B_x \neq B_y$  and  $P_x[X_{xy}] = P_y[X_{xy}]$ , where  $X_{xy} = (X_x \cup B_x) \cap (X_y \cup B_y)$ .

Intuitively, two nodes are connected (*i.e.*, compatible) if their associated derivation rules derive different attributes (*i.e.*,  $B_x \neq B_y$ ), and they agree on the values of their common attributes (*i.e.*,  $P_x[X_{xy}] = P_y[X_{xy}]$ ). Hence these rules have no conflict and can be applied at the same time.

**Example 11:** The compatibility graph of the rules given in Example 10 is shown in Fig. 6. There is an edge  $(n_1, n_2)$  since their common attribute status has the same value *retired*; similarly for the other edges. In contrast, there is no edge between  $n_5$  and  $n_7$  since the values of their common attribute AC are different: 212 for  $n_5$  and 312 for  $n_7$ .  $\square$

Observe that each clique  $\mathcal{C}$  in the compatibility graph indicates a set of derivation rules that can be applied together. Let  $\mathcal{A}'$  be the set of attributes whose true values can be derived from the rules in  $\mathcal{C}$ , if  $\mathcal{C}$  and  $S_e$  have no conflicts (will be discussed shortly). To find a suggestion, we compute a maximum clique  $\mathcal{C}$  from the graph, and define a suggestion as  $(\mathcal{A}, V(\mathcal{A}))$ , where  $\mathcal{A}$  consists of attributes in  $R \setminus (\mathcal{A}' \cup B)$ , and  $V(\mathcal{A})$  is the set of candidate true values for  $\mathcal{A}$ .

**Example 12:** Example 6 shows that for George ( $E_2$ ), only the true values of name and kids are known, *i.e.*,  $B = \{\text{name}, \text{kids}\}$  and  $V_B = (\text{George}, 2)$ . To find a suggestion for George, we identify a clique  $\mathcal{C}_1$  with five nodes  $n_1$ – $n_5$  in the compatibility graph of Fig. 6. Observe the following. (a) The values of job, AC and zip depend on the value of status by rules  $n_1$ ,  $n_2$  and  $n_3$ , respectively. (b) The AC in turn decides city by  $n_5$ . (c) From city and zip one can derive county by  $n_4$ .

---

**Algorithm Suggest**

---

Input: A specification  $S_e = (I_t, \Sigma, \Gamma)$ , order  $O_d (S_e \models O_d)$ , and  $V_B$ .

Output: A suggestion  $(\mathcal{A}, V(\mathcal{A}))$ .

1.  $V(R) := \text{DeriveVR}(I_t, O_d); \quad \Omega(S_e) := \text{Instantiation}(S_e);$
  2.  $\Pi := \text{TrueDer}(\Omega(S_e), V(R)); \quad G := \text{CompGraph}(\Pi, S_e);$
  3.  $\mathcal{C} := \text{MaxClique}(G); \quad \mathcal{A} := \text{GetSug}(S_e, \mathcal{C}, V_B);$
  4. **return**  $(\mathcal{A}, V(\mathcal{A}))$ ;
- 

Fig. 7. Algorithm Suggest

Hence, the set of attributes that can be derived from clique  $\mathcal{C}_1$  is  $\mathcal{A}' = \{\text{job, AC, zip, city, county}\}$ . This yields a suggestion  $(\mathcal{A}, V(\text{status}))$ , where  $\mathcal{A} = R \setminus (\mathcal{A}' \cup \mathcal{B}) = \{\text{status}\}$ , and  $V(\text{status}) = \{\text{retired, unemployed}\}$ . As long as users identify the true value of status, the true value of George exists, and can be automatically deduced as described in Example 9.  $\square$

However,  $\mathcal{C}$  and  $S_e$  may have conflicts, as illustrated below.

**Example 13:** Consider the clique  $\mathcal{C}_2$  of Fig. 6 with three nodes  $n_5, n_6$  and  $n_8$ . Observe the following: (a)  $n_5$  indicates that  $312 \prec_{AC}^v 212$ , since  $212$  is *assumed* the latest AC value; whereas (b)  $n_6, n_8$  and constraint  $\varphi_6$  in Fig. 3 state that  $312$  is the latest AC value, *i.e.*,  $212 \prec_{AC}^v 312$ . These tell us that the values embedded in clique  $\mathcal{C}_2$  may not lead to a valid completion for  $E_2$ , *i.e.*,  $\mathcal{C}_2$  and  $S_e$  have conflicts.  $\square$

To handle conflicts between  $\mathcal{C}$  and  $S_e$ , we use MaxSat to find a maximum subgraph  $\mathcal{C}'$  of  $\mathcal{C}$  that has no conflicts with  $S_e$  (MaxSat is to find a maximum set of satisfiable clauses in a Boolean formula; see *e.g.*, [24]). For instance, for clique  $\mathcal{C}_2$  of Example 13, we use a MaxSat-solver [24] to identify clique  $\mathcal{C}'_2$  with nodes  $n_6$  and  $n_8$ , which has no conflicts with the specification for George. We then derive  $\mathcal{A}' = \{\text{job, zip}\}$  from  $\mathcal{C}'_2$ . Since  $\mathcal{B}$  is  $\{\text{name, kids}\}$  (Example 12), we find  $\mathcal{A} = R \setminus (\mathcal{A}' \cup \mathcal{B}) = \{\text{status, city, AC, county}\}$  for suggestion.

## C.2. Computing Suggestions

We now present the algorithm for computing suggestions, referred to as Suggest and shown in Fig. 7. It takes as input a specification  $S_e$  of  $e$ , partial orders  $O_d$  deduced from  $S_e$  ( $S_e \models O_d$ , by Algorithm DeduceOrder), and the set  $V_B$  of validated true values. It finds and returns a suggestion  $(\mathcal{A}, V(\mathcal{A}))$ .

Algorithm Suggest first computes candidate true values for all attributes whose true values are yet unknown (line 1). It then deduces a set of derivation rules from instance constraints  $\Omega(S_e)$  (line 1) of  $S_e$  (line 2; as illustrated in Example 10). Based on these derivation rules, it builds a compatibility graph (line 2; see Example 11) and identifies a maximum clique  $\mathcal{C}$  in the graph (line 3). Finally, it generates a suggestion using the clique (line 3; see Examples 12 and 13).

We next present the procedures used in the algorithm.

**DeriveVR:** For each  $A \in R$  not in  $V_B$ , it computes  $V(A)$ . Initially  $V(A)$  takes the active domain  $\text{adom}(I_e.A)$ . It then removes all  $a_1 \in \text{adom}(I_e.A)$  from  $V(A)$  if there exists  $a_2 \in \text{adom}(I_e.A) \setminus \{a_1\}$  such that  $a_1 \prec_A^v a_2$  is in the deduced  $O_d$ , as  $a_2$  is more current than  $a_1$  in  $A$ . It takes  $O(|I_t|^2)$  time with an index, since it checks at most  $|O_d|$  orders, and  $|O_d| \leq |I_t|^2$ .

**TrueDer:** Given  $\Omega(S_e)$ , it deduces a set  $\Pi$  of derivation rules. (1) From a constant CFD  $(t_p[X_\varphi] \rightarrow t_p[B_\varphi])$ . We add

$(X_\varphi, t_p[X_\varphi]) \rightarrow (B_\varphi, t_p[B_\varphi])$  to  $\Pi$ , provided that  $t_p[A] \in V[A]$  for each  $A \in X_\varphi \cap \mathcal{B}$ , *i.e.*, when the values of the CFD have no conflict with those validated true values.

(2) From those instance constraints in  $\Omega(S_e)$  that represent currency constraints and currency orders in  $S_e$ . It deduces derivation rules of the form  $(X, P(X)) \rightarrow (B, b)$ , for each attribute  $B$  whose true value is unknown and for each  $b \in V(B)$ , if such a rule exists. While it is prohibitively expensive to enumerate all these rules, we use a heuristics to find a set of derivation rules in  $O(|\Omega(S_e)|)$  time as follows:

- (i) for each  $B$  and  $b \in V(B)$ , let  $U_{(B,b)} = \{b_i \prec_B^v b \mid b_i \in V(B) \setminus \{b\}\}$ , *i.e.*,  $b$  is assumed the true value of  $B$ ;
- (ii) it partitions  $\Omega(S_e)$  based on  $U_{(B,b)}$ : let  $\Omega_{(B,b)}$  consist of  $\phi \in \Omega(S_e)$ , where  $\phi$  is of the form  $\omega \rightarrow b_i \prec_B^v b$ ; note that each  $\phi$  appears in at most one of the partitions;
- (iii) for each  $b_i \in U_{(B,b)}$ , it picks  $\phi = \omega \rightarrow b_i \prec_B^v b$  from  $\Omega_{(B,b)}$  if it exists; it includes those attributes of  $\omega$  in  $X$  and their instantiations in  $P(X)$ , until all  $b_i$ 's in  $U_{(B,b)}$  are covered by such a  $\phi$  (see Example 10 for how  $P(X)$  is populated). Note that  $|X| \leq |R|$ .

The procedure is in  $O((|\Sigma| + |\Gamma|)|I_t|^2 + |I_t|^3)$  time. Indeed, for (1), it is bounded by  $O(|\Gamma|)$ ; and for (2), since  $U_{(B,b)}$ 's are disjoint,  $\Omega_{(B,b)}$ 's partition  $\Omega(S_e)$ , and each  $\phi$  in  $\Omega(S_e)$  is used at most once, the cost is in  $O((|\Sigma| + |\Gamma|)|I_t|^2 + |I_t|^3)$ .

**CompGraph:** Given rules  $\Omega$ , it generates their compatibility graph  $G(N, E)$  (see Example 11). The procedure takes at most  $O(|\Pi|^2)$  time, where  $|\Pi|$  is no larger than  $|R||I_t|$ .

**MaxClique:** It computes a maximum clique  $\mathcal{C}$  of  $G(N, E)$  (an NP-complete problem). Several tools have been developed for computing maximum cliques, with a good approximation bound (*e.g.*, [16]). We use one of these tools as MaxClique.

**GetSug:** Given clique  $\mathcal{C}$ , it computes a suggestion. It first finds the maximal subgraph  $\mathcal{C}'$  of  $\mathcal{C}$  that has no conflicts with  $S_e$ , by using an efficient MaxSat-solver [24] (see Example 13). It then derives a set  $\mathcal{A}'$  of attributes from  $\mathcal{C}'$  (see Example 12). Finally, it returns  $(\mathcal{A}, V(\mathcal{A}))$ , where  $\mathcal{A} = R \setminus (\mathcal{A}' \cup \mathcal{B})$ , and  $\mathcal{B}$  is the set of attributes with validated true values  $V_B$ . Note that the input to the MaxSat-solver is no larger than  $|R|^2|I_t|^2$ .

**Correctness.** Algorithm Suggest guarantees to generate a suggestion  $(\mathcal{A}, V(\mathcal{A}))$ . Indeed, (1) the clique  $\mathcal{C}'$  revised by MaxSat has no conflicts with  $S_e$ , and thus  $\mathcal{C}'$  and  $S_e$  warrant to have a valid completion  $I_t^c$ . Let  $t_c = \text{LST}(I_t^c)$ . If  $V(\mathcal{A})$  are validated for  $\mathcal{A}$ , then  $t_c$  must be the *true value*  $T(S_e)$  of  $S_e$ , since  $t_c[\mathcal{B}] = V_B$  remains unchanged for all valid completions of  $S_e$ , and  $t_c[\mathcal{A}']$  is uniquely determined by  $t_c[\mathcal{A}]$  and  $V_B$  by the construction. (2) All possible true values for  $\mathcal{A}$  from their active domains are already included in  $V(\mathcal{A})$ .

## VI. EXPERIMENTAL STUDY

We conducted experiments with both real-life and synthetic data. We evaluated the accuracy and scalability of (1) IsValid for validating a specification, (2) DeduceOrder for deducing true values, (3) Suggest for computing suggestions, and (4) the overall performance of conflict resolution supporting (1-3).

**Experimental data.** We used two real-life datasets (NBA and CAREER) and synthetic data (Person). Constraints were discovered using profiling algorithms [5], [14], and examined manually. Timestamps for the datasets were either missing (for CAREER and Person) or incomplete (NBA). We assumed *empty currency orders* in all the experiments even when partial timestamps were given. The available (incomplete) timestamps were used for designing currency constraints and verifying the derived true values.

**NBA player statistics.** This dataset was retrieved from (1) <http://databasebasketball.com/>, (2) <http://www.infochimps.com/marketplace>, and (3) [http://en.wikipedia.org/wiki/List\\_of\\_National\\_Basketball\\_Association\\_arenas](http://en.wikipedia.org/wiki/List_of_National_Basketball_Association_arenas). It consists of three tables: (a) Player (from sources 1 and 3) contains information about players, identified by player id (pid). (b) Stat (from 1) includes the statistics of these players from 2005/2006 to the 2010/2011 season. (c) Arenas (from 3) records the historical team names and arenas of each team. We created a table, referred to as NBA, by first joining Player and Stat via *equi-join* on the pid attribute, and then joining Arenas via *equi-join* on the team attribute. The NBA table consists of 19573 tuples for 760 entities (*i.e.*, players). Its schema is (pid, name, true name, team, league, tname, points, poss, allpoints, min, arena, opened, capacity, city). When producing the NBA table we took care of the attributes containing multiple values for a player, *e.g.*, multiple teams for the same player, and multiple teams for one arena. We ensure that only one attribute value (*e.g.*, team) appears in any tuple. Only data from (1) and (3) carries (partial) timestamps. Therefore, the true values of entities in the NBA table *cannot* be directly derived when putting (1), (2) and (3) together.

The number of tuples pertaining to an entity ranges from 2 to 136, about 27 in average. We consider *entity instances*, *i.e.*, tuples referring to the same entity, which are *much smaller* than a database. We found 54 currency constraints: 15 for team names (tname) as shown by  $\varphi_1$  below; 32 for arena, similar to  $\varphi_2$ ; and 4 (resp. 3) for attribute allpoints that were scored since 2005 (resp. arena), similar to  $\varphi_3$  (resp.  $\varphi_4$ ), where  $B$  ranges over points, poss, min and tname (resp. opened, capacity and years). We deduced 58 constant CFDs, *e.g.*, the  $\psi_1$  below. Note that some rules are derived automatically, while the others are designed manually based on the semantics of the data.

$$\begin{aligned} \varphi_1: & \forall t_1, t_2 (t_1[\text{tname}] = \text{"New Orleans Jazz"} \\ & \wedge t_2[\text{tname}] = \text{"Utah Jazz"} \rightarrow t_1 \prec_{\text{tname}} t_2); \\ \varphi_2: & \forall t_1, t_2 (t_1[\text{arena}] = \text{"Long Beach Arena"} \\ & \wedge t_2[\text{arena}] = \text{"Staples Center"} \rightarrow t_1 \prec_{\text{arena}} t_2); \\ \varphi_3: & \forall t_1, t_2 (t_1[\text{allpoints}] < t_2[\text{allpoints}] \wedge t_1[B] \neq t_2[B] \rightarrow t_1 \prec_B t_2) \\ \varphi_4: & \forall t_1, t_2 (t_1 \prec_{\text{arena}} t_2 \wedge t_1[B] \neq t_2[B] \rightarrow t_1 \prec_B t_2) \\ \psi_1: & (\text{arena} = \text{"United Center"} \rightarrow \text{city} = \text{"Chicago, Illinois"}) \end{aligned}$$

**(2) CAREER.** The data was retrieved *as is* from the link <http://www.cs.purdue.edu/commigrate/data/citeseer>. Its schema is (first name, last name, affiliation, city, country). We chose 65 persons from the dataset, and for each person, we collected all of his/her publications, one tuple for each. *No reliable timestamps* were available for this dataset.

The number of tuples pertaining to an entity ranges from 2 to 175, about 32 in average. We derived 503 currency constraints: if two papers  $A$  and  $B$  are by the same person and  $A$  cites  $B$ , then the affiliation and address (city and country) used in paper  $A$  are more current than those used in paper  $B$ . We also deduced a single CFD of the form: (affiliation  $\rightarrow$  city, country), but with 347 patterns with different constants.

The constraints for each dataset (NBA and CAREER) have essentially *the same form*, and *only differ* in their constants, *i.e.*, the number of constraints with different forms is *small*.

**(3) Person data.** The synthetic data adheres to the schema given in Table 2. We found 983 currency constraints (of *the same form* but with distinct constant values for status, job and kid) and a single CFD  $AC \rightarrow$  city with 1000 patterns (counted as distinct constant CFDs), similar to those in Table 3. The data generator used two parameters:  $n$  denotes the number of entities, and  $s$  is the size of *entity instances* (the number of tuples pertaining to an entity). For each entity, it first generated a true value  $t_c$ , and then produced a set  $E$  of tuples that have conflicts but do not violate the currency constraints; we treated  $E \setminus \{t_c\}$  as the entity instance. We generated  $n = 10k$  entities, with  $s$  from 1 to 10k. We used *empty* currency orders here.

**Algorithms.** We implemented the following algorithms in  $C++$ : (a) `IsValid` (Section V-A): it calls MiniSat [19] as the SAT-solver; (b) `DeduceOrder` and `NaiveDeduce`: `NaiveDeduce` repeatedly invokes MiniSat [19], as described in Section V-B; and (c) `Suggest`: it uses MaxClique [16] to find a maximal clique, and MaxSat-solver [24] to derive a suggestion (Section V-C). We simulated user interactions by providing true values for suggested attributes, some with new values, *i.e.*, values not in the active domain. We also implemented (d) `Pick`, a traditional method that randomly takes a value [4]; to favor `Pick`, we picked a value from those that are not less current than any other values, based on currency constraints  $\forall t_1, t_2 (\omega \rightarrow t_1 \prec_A t_2)$  in which  $\omega$  is a conjunction of comparison predicates only, *e.g.*,  $\varphi_1$ - $\varphi_3$  above.

**Accuracy.** To measure the quality of suggestions, we used F-measure (<http://en.wikipedia.org/wiki/F-measure>):

$$F\text{-measure} = 2 \cdot (\text{recall} \cdot \text{precision}) / (\text{recall} + \text{precision}).$$

Here precision is the ratio of the number of values correctly deduced to the total number of values deduced; and recall is the ratio of the number of values correctly deduced to the total number of attributes with conflicts or stale values.

All experiments were conducted on a Linux machine with a 3.0GHz Intel CPU and 4GB of Memory. Each experiment was repeated 5 times, and the average is reported here.

**Experimental results.** We next present our findings. Due to the small size of the CAREER data for each entity, experiments conducted on it took typically less than 10 milliseconds (ms). Hence we do not report its result in the efficiency study.

**Exp-1: Validity checking.** We first evaluated the scalability of `IsValid`. The average time taken by entity instances of various sizes is reported in Fig. 8(a), where the lower  $x$ -axis shows the sizes of NBA, and the upper  $x$ -axis is for Person data. The

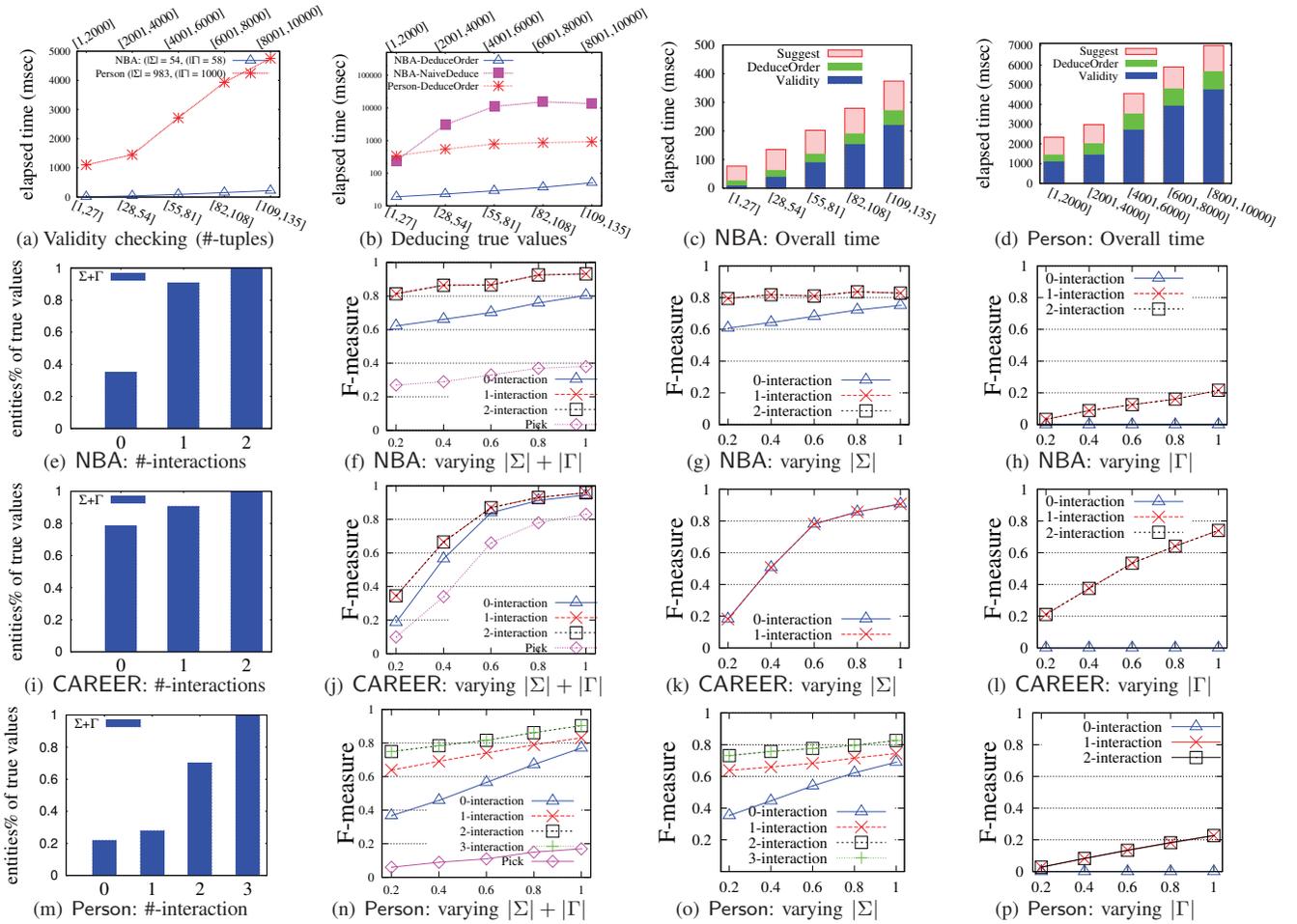


Fig. 8. Experimental results

results show that `lsValid` suffices to validate specifications of a reasonably large size. For example, it took 220 ms for NBA entity instances of 109-135 tuples and 112 constraints, with 14 attributes in each tuple. For Person, it took an average of 4.7 seconds on entities of 8k-10k tuples and 1983 constraints.

We also find `lsValid` accurate (not shown for the lack of space): specifications reported (in)valid are indeed (in)valid.

**Exp-2: Deducing true values.** We next evaluated the performance of algorithms `DeduceOrder` and `NaiveDeduce`. The results on both NBA and Person data are reported in Fig. 8(b), which tell us the following: (a) `DeduceOrder` scales well with the size of entity instances, and (b) `DeduceOrder` substantially outperforms `NaiveDeduce` on both datasets, for reasons given in Section V-B. Indeed, `DeduceOrder` took 51 ms on NBA entity instances with 109-135 tuples, and 914 ms on Person entities of 8k-10k tuples; in contrast, `NaiveDeduce` spent 13585 ms and over 20 minutes (hence not shown in Fig. 8(b)) on the same datasets, respectively.

We also find that `DeduceOrder` derived as many true values as `NaiveDeduce` on both datasets (not shown). This tells us that `DeduceOrder` can efficiently deduce true values on large entity instances without compromising the accuracy.

**Exp-3: Suggestions for user interactions.** We evaluated the accuracy of suggestions generated from currency constraints

$\Sigma$  and CFDs  $\Gamma$  put together. The results on NBA, CAREER and Person are given in Figures 8(e), 8(i) and 8(m), respectively, where the  $x$ -axis indicates the rounds of interactions, and the  $y$ -axis is the percentage of true attribute values deduced.

These results tell us the following. (a) Few rounds of interactions are needed to find all the true attribute values for an entity: at most 2, 2 and 3 rounds for NBA, CAREER and Person data, respectively. (b) A large part of true values can be *automatically deduced* by means of currency and consistency inferences: 35%, 78% and 22% of true values are identified from  $\Sigma + \Gamma$  *without user interaction*, as indicated by the 0-interaction in Figures 8(e), 8(i) and 8(m), respectively.

**Impact of  $|\Sigma|$  and  $|\Gamma|$ .** To be more precise when evaluating the accuracy, we use F-measure, which combines precision and recall, and take the cases of using  $|\Gamma|$  only or  $|\Sigma|$  only into consideration. Figures 8(f)–8(h), 8(j)–8(l) and 8(n)–8(p) show the results for NBA, CAREER and Person, respectively, when varying both  $|\Sigma|$  and  $|\Gamma|$ ,  $|\Sigma|$  only, and varying  $|\Gamma|$  alone, respectively. The  $x$ -axis shows the percentage of  $\Sigma$  or  $\Gamma$  used, and the  $y$ -axis shows the corresponding F-measure values.

These results tell us the following. (a) As shown in Figures 8(f), 8(j) and 8(n), our method substantially outperforms the traditional method `Pick`, by 201% in average on all datasets, even when we favor `Pick` by allowing it to

capitalize on currency orders. This verifies that data currency and consistency can significantly improve the accuracy of conflict resolution. (b) When  $\Sigma$  and  $\Gamma$  are taken together, the F-measure value is up to 0.930 for NBA (Fig. 8(f), the top right point), 0.958 for CAREER (Fig. 8(j)), and 0.903 for Person (Fig. 8(n)), in contrast to 0.830 in Fig. 8(g), 0.907 in Fig. 8(k), and 0.826 in Fig. 8(o), respectively, when  $\Sigma$  is used alone, and as opposed to 0.210 in Fig. 8(h), 0.741 in Fig. 8(l), and 0.234 in Fig. 8(p), respectively, with  $\Gamma$  only. These further verify that the inferences of data currency and consistency should be *unified* instead of taking separately. (c) The more currency constraints and/or CFDs are available, the higher the F-measure is, as expected. (d) The two curves for the 2- and 1-interaction overlap in Figures 8(f)–8(h) for NBA, 2- and 1-interaction in Figures 8(j)–8(l) for CAREER, and 3- and 2-interaction in Figures 8(n)–8(p) for Person. These indicate that the users must provide true values for those attributes that we do not have enough information to deduce their true values.

**Exp-4: Efficiency.** The overall performance for resolving conflicts in the NBA (resp. Person) data is reported in Fig. 8(c) (resp. Fig. 8(d)). Each bar is divided into the elapsed time taken by (a) validity checking, (b) true value deducing, and (c) suggestion generating, including computing the maximal clique and running MaxSat. The result shows that conflict resolution can be conducted efficiently in practice, *e.g.*, each round of interactions for NBA took 380 ms. Here validating specifications takes most time, dominated by the cost of SAT-solver, while deducing true values takes the least time.

**Summary.** We find the following. (a) Conflict resolution with data currency and consistency substantially outperforms the traditional method Pick, by 201%. (b) It is more effective to unify the inferences of data currency and consistency than treating them independently. Indeed, when  $\Sigma$  and  $\Gamma$  are taken together, the F-measure improves over  $\Sigma$  only and  $\Gamma$  only by 11% and 236%, respectively. (c) Our conflict resolution method is efficient: it takes less than 0.5 second on the real-life datasets even with interactions. (d) Our method scales well with the size of entities and the number of constraints. Indeed, it takes an average of 7 seconds to resolve conflicts in Person entity instances of 8k-10k tuples, with 1983 constraints. (e) At most 2-3 rounds of interactions are needed for all datasets.

## VII. CONCLUSION

We have proposed a model for resolving conflicts in entity instances, based on both data currency and data consistency. We have also identified several problems fundamental to conflict resolution, and established their complexity. Despite the inherent complexity of these problems, we have introduced a framework for conflict resolution, along with practical algorithms supporting the framework. Our experimental study has verified that our methods are effective and efficient.

We are now exploring more efficient algorithms for generating suggestions, and testing them with data in various domains. Another topic concerns the discovery of data quality rules. Prior work on discovery of such rules [5] shows that a large

number of high-quality rules can be identified from possibly dirty data. It is also interesting is to repair data by using currency constraints and partial temporal orders. This is more challenging than conflict resolution, since a database to be repaired is typically *much larger* than entity instances. Finally a challenging topic is to extend our framework by allowing users to edit constraints, and by improving the accuracy when users do not have sufficient currency knowledge about their data.

**Acknowledgement.** Fan and Yu are supported in part by the RSE-NSFC Joint Project Scheme and EPSRC EP/J015377/1, UK, and the 973 Program 2012CB316200 and NSFC 61133002, China.

## REFERENCES

- [1] M. Arenas, L. E. Bertossi, and J. Chomicki. Consistent query answers in inconsistent databases. In *PODS*, 1999.
- [2] L. Bertossi. *Database Repairing and Consistent Query Answering*. Morgan & Claypool Publishers, 2011.
- [3] A. Biere, M. Heule, H. van Maaren, and T. Walsh, editors. *Handbook of Satisfiability*, volume 185 of *Frontiers in Artificial Intelligence and Applications*. IOS Press, 2009.
- [4] J. Bleiholder and F. Naumann. Data fusion. *ACM Comput. Surv.*, 41(1), 2008.
- [5] F. Chiang and R. Miller. Discovering data quality rules. In *VLDB*, 2008.
- [6] J. Chomicki and D. Toman. Time in database systems. In *Handbook of Temporal Reasoning in Artificial Intelligence*. Elsevier, 2005.
- [7] G. Cong, W. Fan, F. Geerts, X. Jia, and S. Ma. Improving data quality: Consistency and accuracy. In *VLDB*, 2007.
- [8] U. Dayal. Processing queries over generalization hierarchies in a multidatabase system. In *VLDB*, 1983.
- [9] X. Dong, L. Berti-Equille, and D. Srivastava. Truth discovery and copying detection in a dynamic world. In *VLDB*, 2009.
- [10] X. Dong and F. Naumann. Data fusion - resolving data conflicts for integration. In *VLDB*, 2009.
- [11] W. W. Eckerson. Data quality and the bottom line: Achieving business success through a commitment to high quality data. *The Data Warehousing Institute*, 2002.
- [12] A. K. Elmagarmid, P. G. Ipeirotis, and V. S. Verykios. Duplicate record detection: A survey. *TKDE*, 19(1), 2007.
- [13] W. Fan, F. Geerts, X. Jia, and A. Kementsitsidis. Conditional functional dependencies for capturing data inconsistencies. *TODS*, 33(1), 2008.
- [14] W. Fan, F. Geerts, J. Li, and M. Xiong. Discovering conditional functional dependencies. *TKDE*, 23(5):683–698, 2011.
- [15] W. Fan, F. Geerts, and J. Wijzen. Determining the currency of data. In *PODS*, 2011.
- [16] U. Feige. Approximating maximum clique by removing subgraphs. *SIAM J. Discret. Math.*, 18, February 2005.
- [17] Full version. <http://homepages.inf.ed.ac.uk/s0949090/CR.pdf>.
- [18] A. Galland, S. Abiteboul, A. Marian, and P. Senellart. Corroborating information from disagreeing views. In *WSDM*, 2010.
- [19] E. Giunchiglia and A. Tacchella, editors. *Theory and Applications of Satisfiability Testing*. SAT, 2004.
- [20] S. Greco, C. Sirangelo, I. Trubitsyna, and E. Zumpano. Preferred repairs for inconsistent databases. In *IDEAS*, 2003.
- [21] P. Li, X. Dong, A. Mauricio, and D. Srivastava. Linking temporal records. *PVLDB*, 2011.
- [22] A. Motro and P. Anokhin. Fusionplex: resolution of data inconsistencies in the integration of heterogeneous information sources. *Information Fusion*, 7(2), 2006.
- [23] B. Rob and R. Goldring. Update replication: What every designer should know. In *InfoDB, Vol.9, No.2*, pages 17–24, 1995.
- [24] B. Selman and H. Kautz. Walksat home page, 2004. <http://www.cs.washington.edu/homes/kautz/walksat/>.
- [25] J. Widom. Trio: A system for integrated management of data, accuracy, and lineage. In *CIDR*, 2005.
- [26] M. Yakout, A. K. Elmagarmid, J. Neville, and M. Ouzzani. GDR: a system for guided data repair. In *SIGMOD*, 2010.
- [27] X. Yin, J. Han, and P. S. Yu. Truth discovery with multiple conflicting information providers on the web. *TKDE*, 20(6), 2008.
- [28] H. Zhang, Y. Diao, and N. Immerman. Recognizing patterns in streams with imprecise timestamps. In *VLDB*, 2010.