Extending Dependencies with Conditions

Citation for published version:

Link:
Link to publication record in Edinburgh Research Explorer

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

Published In:
Proceedings of the 33rd International Conference on Very Large Data Bases, University of Vienna, Austria, September 23-27, 2007

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.
Extending Dependencies with Conditions

Loreto Bravo  
University of Edinburgh  
lbravo@inf.ed.ac.uk

Wenfei Fan  
Univ. of Edinburgh & Bell Labs  
wenfei@inf.ed.ac.uk

Shuai Ma  
University of Edinburgh  
smal@inf.ed.ac.uk

Abstract

This paper introduces a class of conditional inclusion dependencies (CINDs), which extends traditional inclusion dependencies (INDs) by enforcing bindings of semantically related data values. We show that CINDs are useful not only in data cleaning, but are also in contextual schema matching [7]. To make effective use of CINDs in practice, it is often necessary to reason about them. The most important static analysis issue concerns consistency, to determine whether or not a given set of CINDs has conflicts. Another issue concerns implication, i.e., deciding whether a set of CINDs entails another CIND. We give a full treatment of the static analyses of CINDs, and show that CINDs retain most nice properties of traditional INDs: (a) CINDs are always consistent; (b) CINDs are finitely axiomatizable, i.e., there exists a sound and complete inference system for implication of CINDs; and (c) the implication problem for CINDs has the same complexity as its traditional counterpart, namely, PSPACE-complete, in the absence of attributes with a finite domain; but it is EXPTIME-complete in the general setting. In addition, we investigate the interaction between CINDs and conditional functional dependencies (CFDs), an extension of functional dependencies proposed in [9]. We show that the consistency problem for the combination of CINDs and CFDs becomes undecidable. In light of the undecidability, we provide heuristic algorithms for the consistency analysis of CFDs and CINDs, and experimentally verify the effectiveness and efficiency of our algorithms.

1. Introduction

A class of conditional functional dependencies (CFDs) has recently been proposed in [9] as an extension of functional dependencies (FDs). In contrast to traditional FDs, CFDs hold conditionally on a relation, i.e., they apply only to those tuples that satisfy certain data-value patterns, rather than to the entire relation. CFDs have proven useful in data cleaning [9]: inconsistencies and errors in the data may emerge as violations of CFDs, whereas they may not be caught by traditional FDs.

It has been recognized [8] that to clean data, one needs not only FDs but also inclusion dependencies (INDs). Furthermore, INDs are commonly used in schema matching systems, e.g., Clio [16]: INDs associate attributes in a source schema with semantically related attributes in a target schema. Both schema matching and data cleaning highlight the need for extending INDs along the same lines as CFDs, as illustrated by the examples below.

Example 1.1: Consider a bank that has branches in various countries. Each branch $B$ maintains a separate account relation:

**source schema:** account$_B$(an, cn, ca, cp, at)

<table>
<thead>
<tr>
<th>an</th>
<th>cn</th>
<th>ca</th>
<th>cp</th>
<th>at</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>J. Smith</td>
<td>NYC, 19087</td>
<td>212-5828844</td>
<td>saving</td>
</tr>
<tr>
<td>02</td>
<td>G. King</td>
<td>NYC, 19022</td>
<td>212-5963455</td>
<td>checking</td>
</tr>
<tr>
<td>03</td>
<td>J. Lee</td>
<td>NYC, 02284</td>
<td>212-5679844</td>
<td>checking</td>
</tr>
</tbody>
</table>

(a) account in NYC branch

<table>
<thead>
<tr>
<th>an</th>
<th>cn</th>
<th>ca</th>
<th>cp</th>
<th>at</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>S. Bundy</td>
<td>EID, RHR 914E</td>
<td>131-6516501</td>
<td>saving</td>
</tr>
<tr>
<td>02</td>
<td>I. Stark</td>
<td>EID, ETD 414P</td>
<td>131-6693234</td>
<td>checking</td>
</tr>
</tbody>
</table>

(b) account in EID branch

<table>
<thead>
<tr>
<th>an</th>
<th>cn</th>
<th>ca</th>
<th>cp</th>
<th>ab</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>J. Smith</td>
<td>NYC, 19087</td>
<td>212-5828844</td>
<td>SYC</td>
</tr>
<tr>
<td>02</td>
<td>G. King</td>
<td>NYC, 19022</td>
<td>212-5963455</td>
<td>SYC</td>
</tr>
<tr>
<td>03</td>
<td>J. Lee</td>
<td>NYC, 02284</td>
<td>212-5679844</td>
<td>NYC</td>
</tr>
</tbody>
</table>

(c) saving

<table>
<thead>
<tr>
<th>an</th>
<th>cn</th>
<th>ca</th>
<th>cp</th>
<th>ab</th>
</tr>
</thead>
<tbody>
<tr>
<td>02</td>
<td>I. Stark</td>
<td>EID, ETD 414P</td>
<td>131-6693234</td>
<td>EID</td>
</tr>
</tbody>
</table>

(d) checking

<table>
<thead>
<tr>
<th>an</th>
<th>cn</th>
<th>ca</th>
<th>cp</th>
<th>at</th>
</tr>
</thead>
<tbody>
<tr>
<td>ab</td>
<td>ct</td>
<td>at</td>
<td>rt</td>
<td></td>
</tr>
<tr>
<td>03</td>
<td>I. Stark</td>
<td>EID, ETD 414P</td>
<td>131-6693234</td>
<td>checking (an, cn, ca, cp, ab) interest (ab, ct, at, rt)</td>
</tr>
</tbody>
</table>

(e) interest

Figure 1: Example account, saving, checking, interest data

in which each tuple specifies an account: the number (an) and type (at, saving or checking) of the account, along with the name (cn), address (ca) and phone number (cp) of the owner of the account.

The bank needs to integrate the account data from its branches and stores the data in a target database with the following schema:

**target schema:**

\begin{align*}
\text{saving} & (an, cn, ca, cp, ab) \\
\text{checking} & (an, cn, ca, cp, ab) \\
\text{interest} & (ab, ct, at, rt)
\end{align*}

where ab is the name of the branch where the account was opened, and an, cn, ca, cp and at are as above. In relation interest, rt indicates the interest rate, and ct is the country where the branch ab is located. Example source (account) and target (saving, checking, interest) data instances are shown in Fig. 1.

A schema matching system might want to match attributes an, cn, ca, cp from source schema account to an, cn, ca, cp in the target schemas saving and checking, and attempt to express the matches in terms of inclusion dependencies from the source to the target, e.g., account$_B$(an, cn, ca, cp) $\subseteq$ saving(an, cn, ca, cp) and account$_B$(an, cn, ca, cp) $\subseteq$ checking(an, cn, ca, cp). These traditional INDs, however, do not make sense: an account in a source relation should be stored either in the target saving or checking, but not in both. This is where we need contextual schema matching [7]: for any tuple $t$ in an account relation, its attributes an, cn, ca, cp can be mapped to the target saving relation only if $t[\text{at}] = \text{saving}$, and to checking only if $t[\text{at}] = \text{checking}$.

To capture this, one can use the constraints below (at branch $B$):

\begin{align*}
\text{ind1:} & \quad \text{account}_B(\text{an}, \text{cn}, \text{ca}, \text{cp}, \text{at} = \text{saving}) \subseteq \text{saving}(\text{an}, \text{cn}, \text{ca}, \text{cp}, \text{ab} = 'B')
\end{align*}
ind_2: account_B (an, cn, ca, cp; at = ‘checking’) \subsetneq
    checking (an, cn, ca, cp; ab = ‘B’)

where ind_1 asserts that for each tuple \( t_1 \) in the account relation at branch \( B \), if \( t_1[ab] = \text{saving} \), then there must exist a tuple \( t_2 \) in saving such that \( t_1[an, cn, ca, cp] = t_2[an, cn, ca, cp] \), and moreover, \( t_2[ab] = B \). That is, an account in the source is migrated to target relation saving only if the type of the account is saving, and in addition, \( t_2[ab] \) holds the constant \( B \). This constraint is an IND that holds only on the subset of account tuples that satisfy the pattern at = ‘saving’, rather on the entire account relation; similarly for ind_2. However, these constraints are not considered INDs since they are specified with a pattern containing data values. □

Example 1.2: Next let us focus on the target database alone and consider data cleaning. It has been recognized that integrity constraints are important in data cleaning [24]. Prior work on constraint-based data cleaning, however, mostly adopts traditional dependencies such as FDs and INDs (e.g., [2, 8, 13, 25]). Traditional FDs and INDs on our example database include:

- \( \text{fd}_1: \text{saving} (an, ab \rightarrow cn, ca, cp) \)
- \( \text{fd}_2: \text{checking} (an, ab \rightarrow cn, ca, cp) \)
- \( \text{fd}_3: \text{interest} (ct \rightarrow rt) \)
- \( \text{ind}_1: \text{saving} (ab) \subseteq \text{interest} (ab) \)
- \( \text{ind}_2: \text{checking} (ab) \subseteq \text{interest} (ab) \)

These assert that an, ab are a key for saving and checking (\( \text{fd}_1, \text{fd}_2 \)), all the saving (resp. checking) accounts in the same country must have the same interest rate (\( \text{fd}_3 \)), and that any branch in saving and checking must appear in interest (\( \text{ind}_1, \text{ind}_2 \)).

While the instances of Fig. 1 satisfy these traditional dependencies, the data is not clean. The bank may offer slightly different interest rates for accounts in different countries, e.g., for checking accounts in the UK, the interest rate is 1.5%, whereas it is 1% for the US checking accounts. Tuple \( t_{12} \) in Fig. 1(e) indicates that the interest rate for checking accounts in the UK is 10.5% rather than 1.5%. This inconsistency, however, cannot be detected by standard INDs and FDs, which were originally developed for schema design rather than data cleaning. In contrast, this can be caught by the constraints below, which refine \( \text{ind}_1 \) and \( \text{ind}_2 \) by adding patterns:

- \( \text{ind}_3: \text{saving} (ab = \text{‘EDI’}) \subseteq \text{interest} (ab = \text{‘EDI’}, at = \text{‘saving’}, ct = \text{‘UK’}, rt = 4.5\%) \)
- \( \text{ind}_4: \text{checking} (ab = \text{‘EDI’}) \subseteq \text{interest} (ab = \text{‘EDI’}, at = \text{‘checking’}, ct = \text{‘UK’}, rt = 1.5\%) \)
- \( \text{ind}_5: \text{saving} (ab = \text{‘NYC’}) \subseteq \text{interest} (ab = \text{‘NYC’}, at = \text{‘saving’}, ct = \text{‘US’}, rt = 4\%) \)
- \( \text{ind}_6: \text{checking} (ab = \text{‘NYC’}) \subseteq \text{interest} (ab = \text{‘NYC’}, at = \text{‘checking’}, ct = \text{‘US’}, rt = 1\%) \)

\( \text{ind}_3 \) says that for each Edinburgh checking account, there must exist a tuple \( t \) in interest such that \( t[ab] = \text{EDI}, t[ct] = \text{checking}, t[rt] = \text{UK} \) and \( t[rt] = 1.5\% \). Thus tuple \( t_{12} \) violates \( \text{ind}_3 \); no interest tuple matches \( t_{12} \) with the correct interest rate 1.5%. This shows that \( \text{ind}_3 \) catches the error that is not detected by traditional FDs and INDs. In fact, \( \text{ind}_6 \) and \( \text{fd}_3 \) together assure that for all Edinburgh checking accounts, 1.5% is the unique interest rate. □

Dependencies such as \( \text{ind}_1 \) – \( \text{ind}_4 \) and \( \text{ind}_5 \) – \( \text{ind}_6 \) apply conditionally to relations. Clearly, such constraints are needed for both schema matching and data cleaning, and hence deserve a full treatment. However, they cannot be expressed as standard INDs.

Contributions. To this end we introduce an extension of INDs and investigate the static analysis of these constraints.

Our first contribution is a notion of conditional inclusion dependencies (CINDs). A CIND is defined as a pair consisting of an IND \( R_1[X] \subseteq R_2[Y] \) and a pattern tableau, where the tableau enforces binding of semantically related data values across relations \( R_1 \) and \( R_2 \). For example, \( \text{ind}_1 \) – \( \text{ind}_6 \) given above can be expressed as CINDs. In particular, traditional INDs are a special case of CINDs. This mild extension of INDs captures a fundamental part of the semantics of data, and suffices to express many applications commonly found in data cleaning and schema matching.

Our second contribution consists of techniques for reasoning about CINDs. Given a set of CINDs, the first thing one wants to do is to determine whether the CINDs are consistent, i.e., whether they have conflicts. This is very important: one does not want to enforce the CINDs on a database at run-time but find, after repeated failures, that the CINDs cannot possibly be satisfied by a nonempty database. Similarly, one does not want to match schema based on CINDs that do not make sense. The consistency analysis helps users to develop consistent sets of CINDs for data cleaning and schema matching. For traditional INDs and FDs, consistency is not an issue: one can specify any INDs and FDs without worrying about their consistency. In contrast, it is known that CFDs may have conflicts, and that it is intractable to decide whether or not a set of CFDs is consistent [9]. Another decision problem associated with CINDs is the implication problem, which is to decide whether a set of CINDs entails another CIND. For traditional INDs, the implication problem is PSPACE-complete. Furthermore, it is finitely axiomatizable: there exists a finite, sound and complete set of axioms. The implication analysis is useful in reducing redundant CINDs, and hence improving performance when detecting CIND violations in a database, and speeding up the derivation of schema mappings from CINDs [16].

We show that although CINDs are more expressive than INDs, they retain most nice properties of their traditional counterpart: (a) CINDs are always consistent; (b) the implication of CINDs is finitely axiomatizable; (c) in the absence of attributes with a finite domain, the implication problem for CINDs is also PSPACE-complete, while in the general setting, it is EXPTIME-complete. Since a problem with a PSPACE lower bound is already beyond reach in practice, the EXPTIME result actually tells us that we do not have to pay too high a price for the increased expressive power of CINDs.

Our third contribution is an investigation of the interaction between CINDs and CFDs. This is necessary: in data cleaning one needs both CFDs and CINDs; so does in schema matching where one needs CINDs and at least conditional keys [16], a special case of CFDs. For traditional FDs and INDs, the interaction is already intriguing: the implication problem for FDs and INDs is undecidable and is not finitely axiomatizable. The interaction between CINDs and CFDs makes our lives even harder: we show that for CINDs and CFDs together, the consistency problem is undecidable.

Our fourth contribution is a set of algorithms for checking the consistency of CFDs and CINDs. In light of the undecidability result mentioned above, any consistency-checking algorithm for CFDs and CINDs that runs in polynomial times is necessarily heuristic. That is, the algorithm is sound on detecting consistent sets of CINDs and CFDs, but not necessarily complete. Our heuristic algorithms are based on a combination of chase techniques, dependency-graph analysis, and bounded-size witness database construction.

Our fifth and final contribution is a preliminary experimental study. We compare the performances of our algorithms in terms of both the accuracy of output and evaluation time. Our experimental results show that our algorithms are effective and efficient.

These results provide not only complexity bounds and an inference system for fundamental problems associated with CINDs (and CFDs), but also efficient algorithms that allow CINDs and CFDs to be used in practice. Our conclusion is that CINDs, together with CFDs, may lead to promising tools for cleaning data and for finding quality schema matches.
We should remark that CINDs do not introduce a new logical formalism. Indeed, in first-order logic, they can be expressed in a form similar to tuple-generating dependencies (TGDs), which have lately generated renewed interests in schema mapping (see [18] for a survey on recent results). However, (a) these simple CINDs suffice to capture data consistency and contextual schema matching commonly found in practice, without incurring the complexity of full-fledged TGDs; (b) no prior work has studied the consistency, implication and finite axiomatizability problems for TGDs in the presence of constants (data values).

**Organization.** We define CINDs in Section 2, and investigate their associated consistency and implication problems in Section 3. In Section 4 we study the consistency analysis of CINDs and CFDs, and provide heuristic algorithms in Section 5. Our experimental results are presented in Section 6, followed by related work in Section 7 and conclusion in Section 8.

## 2. Conditional Inclusion Dependencies

A relational database schema $\mathcal{R}$ is a collection of relation schemas $(R_1, \ldots, R_m)$, where each $R_i$ is defined over a fixed set of attributes $\text{attr}(R_i)$. Each attribute $A_k$ has an associated domain, $\text{dom}(A_k)$, which is finite or infinite. The set $\text{finattr}(\mathcal{R})$ contains the finite attributes of $\mathcal{R}$. An instance $I$ of $\mathcal{R}$ is a set of tuples such that for each $i \in I$, $t[A_k] \in \text{dom}(A_k)$ for each attribute $A_k \in \text{attr}(R_i)$. A database instance $D$ of $\mathcal{R}$ is a collection of relations $(t_1, \ldots, t_n)$, where $I$ is an instance of $R_i$ for $i \in [1, n]$.

### Syntax.

A conditional inclusion dependency (CIND) $\psi$ is a pair $(R_1[X,P] \subseteq R_2[Y,P], T_3)$, where $(1) \; X, X'$, and $Y$ are lists of attributes in $\text{attr}(R_1)$ and $\text{attr}(R_2)$, respectively, such that $X$ and $X'$ are disjoint; $(2) \; R_1[X] \subseteq R_2[Y]$ is a standard IND, referred to as the IND embedded in $\psi$; and $(3) \; T_3$ is a tableau, called the pattern tableau of $\psi$; it has all attributes in $X, X'$, and $Y$. Each $A \in \text{attr}(\mathcal{R})$ is a standard IND.

### Example 2.1.

Constraints $\text{ind}_1$–$\text{ind}_4$ given in Examples 1.1 and 1.2 can all be expressed as CINDs shown in Fig. 2: $\psi_1$–$\psi_4$. For each $\text{ind}_i$–$\text{ind}_4$, respectively, $\psi_i$ for both $\text{ind}_1$ and $\text{ind}_4$, one pattern tuple for each constraint; and $\psi_i$ for both $\text{ind}_2$ and $\text{ind}_3$. In $\psi_1$, for instance, both $X$ and $Y$ are $\text{an}, \text{cn}, \text{ca}, \text{cp}$, $X'$ is $\{\text{at}\}$ and $Y'$ is $\{\text{ab}\}$. In $\psi_2$, both $X$ and $Y$ are $\{\text{an}, \text{cn}, \text{ca}, \text{cp}\}$, while both $X'$ and $Y'$ are $\{\text{ab}\}$. In $\psi_3$, both $X$ and $Y$ are $\{\text{an}, \text{cn}, \text{ca}, \text{cp}\}$, while both $X'$ and $Y'$ are $\{\text{ab}, \text{at}, \text{ct}, \text{rt}\}$.

As shown by $\psi_3$ and $\psi_4$, a standard IND $R_1[X] \subseteq R_2[Y]$ is a special case of the CIND $(R_1[X, X'] \subseteq R_2[Y, Y'], T_3)$ in which both $X'$ and $Y'$ are nil, and $T_3$ has a single tuple with $'\psi'$ only.

### Semantics.

In general the IND embedded in a CIND may not hold on the entire $R_1$ relation; it applies only to $R_1$ tuples matching the pattern tuples. More precisely, we define an order $\preceq$ on data values and the unnamed variable $'\psi'$: $\eta_1 \preceq \eta_2$ if either $\eta_1 = \eta_2$, or $\eta_1$ is a data value and $\eta_2$ is $'\psi'$. The order $\preceq$ naturally extends to tuples, e.g., (EDI, UK, 1.5%) $\preceq$ (EDI, UK, 4.5%) but (EDI, UK, 4.5%) $\not\preceq$ (EDI, UK, 10.5%). We say that a tuple $t_1$ matches $t_2$ if $t_1 \preceq t_2$.

An instance $(t_1, t_2)$ of $(R_1, R_2)$ satisfies the CIND $\psi$, denoted by $(t_1, t_2) \models \psi$, if for each $t_1$ in the relation $R_1$, and for each tuple $t_2$ in the pattern tableau $T_3$, if $t_1[X,X'] \preceq t_2[X,X']$, then there exists $t_2$ in the relation $R_2$ such that $t_1[X,X'] \preceq t_2[X,X']$.

### Example 2.2.

The database in Fig. 1 satisfies CFDs $\psi_1$–$\psi_7$. Note that although these CINDs are satisfied, their embedded INDs do not necessarily hold. For example, while $\psi_1$ is satisfied, the IND $\text{account}\_\text{edi}[\text{an}, \text{cn}, \text{ca}, \text{cp}] \subseteq \text{saving}[\text{an}, \text{cn}, \text{ca}, \text{cp}, \text{ab}]$ is not. The pattern $X_6$ in $\text{LHS}(\psi_1)$ is used to identify the tuples over which $\psi_1$ has to be enforced, namely, tuples for saving accounts.

On the other hand, $\psi_6$ is violated by the database. Indeed, for tuple $t_{10}$, there exists a pattern tuple $\psi_6$ (the first tuple) in $T_6$ such that $t_{10}[\text{ab}] \preceq \psi_6[\text{ab}]$ but there is no tuple $t$ in table $\text{ct}$ such that $t[\text{ab}] = \text{EDI}, t[\text{at}] = \text{checking}, t[\text{cn}] = \text{UK}$ and $t[\text{rt}] = 1.5\%$.

We say that a database $D$ satisfies a set $\Sigma$ of CINDs, denoted by $D \models \Sigma$, if $D \models \psi$ for each $\psi \in \Sigma$.

## 3. Reasoning about CINDs

With any constraint language $L$, there are two associated fundamental problems: the consistency problem for determining whether a given set of constraints in $L$ has conflicts, and the implication problem for deriving other constraints from a given set of constraints in $L$. As remarked in Section 1, for constraints in a language to be effectively used in practice, it is often necessary to be able to answer these two questions at compile time.

One might be tempted to use a constraint language more powerful than CINDs, e.g., full-fledged TGDs extended by allowing constants (data values). The question is whether the language allows us to effectively reason about its constraints. We need a constraint language that is powerful enough to express dependencies commonly
found in schema matching and data cleaning, while at the same
time well-behaved enough so that its associated decision problems
are tractable or, at the very least, decidable [18]. For full-fledged
TGDs, it was known 30 years ago that the implication problem is
undecidable even in the absence of data values [5].

As found in most database textbooks, standard INDS have several
nice properties. (a) INDS are always consistent. (b) For INDS, the
implication problem is decidable (PSpace-complete). (c) Better
still, INDS are finitely axiomatizable, i.e., there exists a finite infer-
sion system that is sound and complete for implication of INDS.
The question is: when constants are introduced into INDS as found
in CINDs, does the extension of INDS still has these properties?

Example 3.1: Consider a schema \( R \) with\( att(R) = \{ A, B \} \), and
the CFDs below on \( R \), refining standard INDS \( A \rightarrow B \) and \( B \rightarrow A: \)
\[
\phi_1: (A = \text{true}) \rightarrow (B = b_1), \quad \phi_2: (A = \text{false}) \rightarrow (B = b_2),
\phi_3: (B = b_1) \rightarrow (A = \text{false}), \quad \phi_4: (B = b_2) \rightarrow (A = \text{true}),
\]
where \( \text{dom}(A) \) is bool, and \( b_1, b_2 \) are two distinct constants in \( \text{dom}(B) \). CFD \( \phi_1 \) (resp. \( \phi_2 \)) asserts that for any tuple \( t \), if \( t[A] \) is true (resp. false), then \( t[B] \) must be \( b_1 \) (resp. \( b_2 \)). On the other
hand, \( \phi_3 \) (resp. \( \phi_4 \)) requires that if \( t[B] \) is \( b_1 \) (resp. \( b_2 \)), then \( t[A] \) must be false (resp. true). There exists no nonempty instance of \( R \)
satisfying all these CFDs. Indeed, for any \( R \) tuple \( t \), no matter what
Boolean value \( t[A] \) has, these CFDs together force \( t[A] \) to take
the other value from the finite domain bool.

Note that if \( \text{dom}(A) \) and \( \text{dom}(B) \) were infinite, we could find a
tuple \( t \) such that \( t[A] \) is neither true nor false, and \( t[B] \) is neither \( b_1 \) nor \( b_2 \); then the \( R \) instance \{ \( t \) \} satisfies these CFDs. This tells us that
attributes with a finite domain may complicate the analysis.

It was shown in [9] that the consistency problem for CFDs is
NP-complete. As opposed to CFDs, we show that for CINDs the
consistency analysis is as trivial as their standard counterpart.

Theorem 3.2: For any set \( \Sigma \) of CINDs defined on a schema \( R \), there
exists a nonempty instance \( D \) of \( R \) such that \( D \models \Sigma \).

Proof Sketch: Given \( \Sigma \), one can construct an instance of \( R \) as
follows. First define an active domain for each attribute \( A \in R \),
consisting of the constants appearing in \( \Sigma \) plus at most one distinct
value in \( \text{dom}(A) \). Then, build an instance of each relation schema
in \( R \) as the cross product of the active domains of all attributes
in it. This yields a nonempty instance of \( R \) satisfying \( \Sigma \).

3.2 Implication and Finite Axiomatization of CINDs

The implication problem for CINDs is to determine, given a finite set
of CINDs and another CIND \( \psi \) defined on a database schema \( R \), whether or not \( \Sigma \) entails \( \psi \), denoted by \( \Sigma \models \psi \), i.e., whether or not for all instances \( D \) of \( R \), if \( D \models \Sigma \) then \( D \models \psi \).

Example 3.3: Let \( \Sigma \) be the set of CINDs given in Fig. 2, and assume
that \( \text{dom}(at) = \{ \text{saving}, \text{checking} \} \). One wants to know whether
\( \Sigma \models \psi \), where \( \psi = (\text{account}_B[\text{at}; \text{nil}] \subseteq \text{interest}[\text{at}; \text{nil}] \cup [\text{at}];) \), i.e., whether or not \( \psi \) is derivable from \( \Sigma \).

As remarked earlier, for standard INDS the implication problem is
not only decidable but also finitely axiomatizable. The finite
axiomatizability is a property stronger than the decidability since
inference rules reveal the essential properties of the constraints.

We now show that CINDs are also finitely axiomatizable. We
provide an inference system for CINDs, denoted by \( I \) and shown
in Fig. 3. Given a finite set \( \Sigma \) of CINDs and another CIND \( \psi \), we
denote by \( \Sigma \vdash I \psi \) that \( \psi \) is provable from \( \Sigma \) using \( I \). The
rules in \( I \) characterize CIND implication: they are both sound, i.e., if
\( \Sigma \vdash I \psi \) then \( \Sigma \models \psi \), and complete, i.e., if \( \Sigma \models \psi \) then \( \Sigma \vdash I \psi \).

Theorem 3.3: The inference system \( I \) is sound and complete for
implication of CINDs.

Proof Sketch: The soundness of \( I \) is verified by induction on the
length of \( I \)-proofs, and its completeness is shown by using a chase
technique (see, e.g., [1] for the details of chase).

Recall that for standard INDS, the inference system proposed in
Furthermore, since a variable in the pattern portion of the CIND has no effect, we can just delete A from the CIND.

CIND8 is, in a way, the inverse of CIND4. If CIND4 is used over a CIND ψ to instantiate the values in the pattern tuple for attributes A and B when t[ψ] ranges over all the values of dom(ψ), then CIND8 can take all those CINDs and restore ψ. In short, CIND8 merges a set of CINDs if (1) they differ only in the value of t[ψ], (2) t[ψ] ranges over all the values in dom(ψ), and (3) there is an attribute B in the RHS of each CIND such that t[ψ][B] = t[B].

Example 3.4: Recall Σ and ψ from Example 3.3, where dom(at) = {checking,saving}. We show that Σ ⊢₂ ψ; then from Theorem 3.3 it follows that Σ |= ψ.

1. (account_A in [ψ] nil, ab at) ≡ checking nil, ab, t₁₁, CIND2
t₁₁ = (saving) (B)
2. (account_A in [ψ] nil, ab at) ≡ checking nil, ab, t₁₂, CIND2
t₁₂ = (checking) (B)
3. (saving nil, ab) ≡ interest nil, at, t₁₃, CIND2
t₁₃ = (saving)
4. (checking nil, ab) ≡ interest nil, at, t₁₄, CIND2
t₁₄ = (checking)
5. (account_A in [ψ] nil, ab at) ≡ checking nil, t₁₅, CIND2
t₁₅ = (checking)
6. (account_A in [ψ] nil, ab at) ≡ checking nil, t₁₆, CIND2
t₁₆ = (checking)

It is not surprising that the implication problem of CINDs is harder than standard INDs. The lower bound of the theorem below is verified by reduction from the two-player tiling problem [12].

Theorem 3.4: The implication problem for CINDs is EXPSPACE-complete.

The complication of the implication problem arises from examining attributes with a finite domain. In the absence of such attributes, there is a linear-space non-deterministic algorithm that uses only rules CIND1–CIND6 in Σ. In this case, the implication problem for CINDs has precisely the same complexity as its IND counterpart, namely, the problem becomes PSPACE-complete.

Theorem 3.5: For any set Σ ⊃ σ of CINDs defined on a schema R, it is PSPACE-complete to decide whether or not Σ ⊢ σ; if neither Σ nor σ involves R attributes that have a finite domain. In this setting, the inference rules CIND1–CIND6 are sound and complete for implication of CINDs.
φ_1 = (saving (an, ab → cn, ca, cp), T'_1)

T'_1:  
- an - ab - cn - ca - cp

φ_2 = (checking (an, ab → cn, ca, cp), T'_2)

φ_3 = (interest (ct, at → rt), T'_3)

c_{fix}:

<table>
<thead>
<tr>
<th>ct</th>
<th>at</th>
<th>rt</th>
</tr>
</thead>
<tbody>
<tr>
<td>UK</td>
<td>saving</td>
<td>4.5%</td>
</tr>
<tr>
<td>UK</td>
<td>checking</td>
<td>1.5%</td>
</tr>
<tr>
<td>US</td>
<td>saving</td>
<td>4%</td>
</tr>
<tr>
<td>US</td>
<td>checking</td>
<td>1%</td>
</tr>
</tbody>
</table>

Figure 4: Example CFDs

Example 4.1: The FDs fd_1, fd_2 given in Example 1.2 can be expressed as CFDs, as shown in Fig. 4. This tells us that standard FDs are a special case of CFDs in which the pattern tableau contains a single tuple that consists of “*” only.

We can refine fd_1 by asserting that when ct is UK (resp. US) and at is saving, rt must be 4.5% (resp. 4%); similarly, if ct is UK (resp. US) and at is checking, rt must be 1.5% (resp. 1%). These are incorporated into φ_2 of Fig. 4 (the last 4 tuples, one per constraint).

While the instance of Fig. 1 satisfies standard FDs fd_1, fd_2 and it satisfies φ_1 and φ_2, it does not satisfy φ_3. Indeed, tuple t_{12} of Fig. 1 violates the constraint specified by the third pattern tuple t_{12}' in T'_3: although t_{12}(ct, at) = t_{12}'(ct, at), we can see that t_{12}[rt] ≠ t_{12}'[rt]; t_{12}[rt] is 10.5% but t_{12}'[rt] is 1.5%. From this we can see that while it takes at least two tuples to violate a standard FD, a single tuple alone may violate a CFD. Moreover, CFDs can catch inconsistencies that standard FDs cannot detect.

Along the same lines as CINDs in normal form, we say that a CFD \( \phi = (R : X \rightarrow Y) \) is in the normal form if \( T_\phi \) consists of a single tuple \( t_\phi \) and \( Y \) contains a single attribute \( A \), and we write \( \phi \) as \( (R : X \rightarrow A) \). We can always rewrite a CFD into an equivalent set of CFDs in the normal form. In the sequel, we only consider CFDs in the normal form.

For CFDs the following have been established in [9]. (a) The consistency problem for CFDs is NP-complete. (b) The implication problem of CFDs is finitely axiomatizable. (c) The implication problem for CFDs is coNP-complete. (d) The consistency and implication problems are in \( \text{O}(n^2) \) time, where \( n \) is the size of the given CFDs, if the CFDs do not involve attributes with a finite domain.

While CFDs alone already complicate the static analyses, we next show that CFDs and CINDs together make our lives much harder.

**Implication analysis.** It is not surprising that the implication problem for CINDs and CFDs is undecidable and is not finitely axiomatizable, since the problems already have these characteristics for standard INDs and FDs (see, e.g., [1]), and CINDs and CFDs subsume INDs and FDs, respectively. The result holds if the given constraints do not involve attributes with a finite domain.

**Corollary 4.1:** The implication problem for CINDs and CFDs is undecidable, and is not finitely axiomatizable, even for CINDs and CFDs that involve only attributes with an infinite domain.

**Consistency analysis.** Even if a set of CFDs and a set of CINDs are separately consistent, when they are put together, there may be conflicts among them, as illustrated below.

**Example 4.2:** Consider a relation \( R \) with \( \text{attr}(R) = \{A, B\} \), on which we define a CFD \( \phi = (R : A \rightarrow B, (\_)[a]) \) and a CIND \( \psi = (R[\text{nil}][B] \subseteq R[\text{nil}][B], (\_)[b]) \), where \( a \) and \( b \) are distinct constants. Obviously, there exists a nonempty instance of \( R \) that satisfies \( \phi \) and there is an instance satisfying \( \psi \). However, there exists no nonempty instance of \( R \) that satisfies both \( \phi \) and \( \psi \). To see this, assume that such an instance \( D \) exists. Then \( \psi \) tells us that as long as \( D \) is nonempty, there is a tuple \( t \) in \( D \) such that \( t[B] = b \).

While the undecidability of the implication problem for CINDs and CFDs is expected, the following result is a little surprising. The undecidability can be verified by reduction from the implication problem for standard FDs and INDs. The undecidability remains intact in the absence of attributes with a finite domain.

**Theorem 4.2:** The consistency problem for CFDs and CINDs is undecidable, with or without attributes having a finite domain.

This tells us that it is necessary to use heuristic methods to solve the consistency and implication problems in practice.

**Summary.** We summarize the complexity bounds for the consistency and implication problems, as well as for finite axiomatizability (Fin. Axiom) in Tables 1 and 2. Table 1 gives the results in the general setting where attributes of infinite domains and those with finite domains are both present, and Table 2 for constraints involving attributes with an infinite domain only. This gives us a complete picture of the static analyses for CINDs and CFDs, established in this work (for CINDs, and CINDs + CFDs) and in [9] (for CFDs).

### 5. Algorithms for Consistency Analysis

In light of the undecidability of the consistency problem for CINDs and CFDs, in this section we develop efficient heuristic methods to check the consistency of CINDs and CFDs.

More specifically, given a set \( \Sigma \) of CINDs and CFDs, our algorithms attempt to construct a nonempty witness database \( D \) such that \( D \models \Sigma \). The algorithms conclude that \( \Sigma \) is consistent, and return true, if such a witness can be built. It is guaranteed that if true is returned then \( \Sigma \) is consistent. However, the algorithms might not find a witness database even if \( \Sigma \) is consistent, due to the undecidability of the problem. As will be seen in the next section, the algorithms are able to return accurate answers in most cases.

The algorithms are based on an extension of the chase technique, bounded-size witness databases, and an optimization technique leveraging dependency graphs of CINDs and CFDs. We extend the chase in Section 5.1, present a checking algorithms in Section 5.2 and provide our optimization technique in Section 5.3.

#### 5.1 Chasing with CFDs and CINDs

The chase is an important tool for implication analysis of dependencies and for query optimization (see, e.g., [1] for details about chase). However, even for standard INDs there may be infinite chasing sequences, i.e., the chase may not terminate. To cope with this, we present an extension of the chase that, employs tables with bounded-size, therefore, guaranteeing termination. We use this extension of the chase for the consistency analysis of CFDs
Consider a database schema $\mathcal{R}$. For each relation schema $R$ in $\mathcal{R}$ and each attribute $A$ in $R$, we assume a nonempty finite set $\text{var}[A]$ of distinct variables. Intuitively, when chasing with $\text{CINDs}$, we may have to create a new tuple; then we use only the variables in these sets to "populate" the unknown fields in the tuple. All the sets $\text{var}[A]$ have a maximum size of $N$, which is a predefined parameter.

Let $\mathcal{V}$ be the set consisting of all these variables. We assume for convenience a total order $\prec$ on variables in $\mathcal{V}$. We also assume that $v \prec a$ for any $v \in \mathcal{V}$ and constant $a$, but do not pose the order on constants. Thus $v \neq a$ and $v \neq a'$; but we allow $v \sim a'$.

We now define our chase operations for a set $\Sigma$ of CINDs and CFDs, which transform a database $D$ into a new database $D'$. To simplify the discussion we denote by $R$ a schema as well as an instance of the schema when it is clear from the context.

For each CIND $\psi = (R_1,A_1,\ldots,A_m; X_p) \subseteq R_2[B_1,\ldots,B_m; Y_p]; t_p)$ in $\Sigma$, we define the chase operation $\text{IND}(\psi)$ as follows. For a tuple $t_0 \in R_0$ satisfying $t_0[X_p] = t_p[X_p]$, we add a tuple $t_0$ to $R_0$ such that $t_0[B_i] = t_0[A_i]$ for $i \in [1,m]$, $t_0[Y_p] = t_p[Y_p]$, and $t_0[B]$ takes a random variable from $\text{var}[B]$ for the rest attribute $B \in \text{attr}(R_0) - \{(B_1, B_2) \cup \mathcal{Y}p\}$.

For each CFD $\phi = (R : X \rightarrow A, t_p) \in \Sigma$, we define the chase operation $\text{FD}(\phi)$ as follows. For tuples $t_1, t_2 \in R$ such that $t_1[X] = t_2[X] \times t_2[X]$, but either $t_1[A] \neq t_2[A]$ or $t_1[A] = t_2[A] \neq t_p[A]$, we consider the following two cases: (i) $t_1[A] = \mathcal{W}$: if either $t_1[A]$ or $t_2[A]$ is a variable and $t_1[A] < t_2[A]$ (resp. $t_2[A] < t_1[A]$), then we replace $t_1[A]$ with $t_2[A]$ in $R$ (resp. replace $t_2[A]$ with $t_1[A]$). If $t_1[A]$ and $t_2[A]$ are different constants, then the application of $\text{FD}(\phi)$ to $D$ is not defined. (ii) $t_1[A] = a$: if either $t_1[A]$ or $t_2[A]$ is a constant distinct from $a$, then the application of $\text{FD}(\phi)$ is undefined. Otherwise we replace both $t_1[A]$ and $t_2[A]$ with $a$.

A chasing sequence of $D$ w.r.t. $\Sigma$ is a sequence of database templates (with variables) $D_0, D_1, \ldots, D_n$ such that $D_0 = D$ and $D_{n+1}$ is the result of applying a chase operation for a constraint in $\Sigma$ to $D_n$. If $\text{IND}(\psi)(D_n) = D_n$ for every CIND $\psi \in \Sigma$ and $\text{FD}(\phi)(D_n) = D_n$ for every CFD $\phi \in \Sigma$, we say that the chase of $\Sigma$ over $D$ is terminal and refer to $D_n$ as the result of the chase, denoted by chase($D, \Sigma$). Otherwise, $\text{FD}(\phi)$ must be undefined for some $\phi \in \Sigma$, and in this case we say that chase($D, \Sigma$) is undefined. Since the chase takes values from a predefined finite set of variables, it will always terminate. Note that for a set of CINDs only, the chase is always defined.

5.2 Heuristic Methods for Consistency Checking

Employing this extension of the chase, we next develop a heuristic method for checking the consistency of CINDs and CFDs.

For any set $\Sigma$ of CINDs and CFDs defined over $\mathcal{R}$, if $\Sigma$ does not involve attributes that have finite domains, a possible heuristic to determine if $\Sigma$ is consistent works as follows: (1) it first constructs a database $D$ that only contains, in a randomly chosen relation $R \in \mathcal{R}$, a tuple $t = (v_1, \ldots, v_n)$ such that $t[A] = v_i$ from $\text{var}[A]$; (2) it then checks whether chase($D, \Sigma$) is defined; and (3) it return true if the chase is defined. One can see that if chase($D, \Sigma$) is defined then $\Sigma$ is consistent, as illustrated by the example below.

Example 5.1: Consider $\mathcal{R} = (R_1, R_2)$, where attr($R_1$) = {E, F}, attr($R_2$) = {G, H}, finattr($\mathcal{R}$) = \emptyset, and the domain of all the attributes is string. Also consider $\Sigma = \{(\phi_1, \phi_2, \psi_1, \psi_2, \psi_3)\}$, where $\phi_1 = (R_1 : \mathcal{E} \rightarrow \mathcal{F}, (x[\mathcal{E}]), \phi_2 = (R_2 : \mathcal{H} \rightarrow \mathcal{G}, (x[\mathcal{H}]), \psi_1 = (R_3[\mathcal{E}, \mathcal{I}] \subseteq R_2[\mathcal{G}, \mathcal{I}], (x[\mathcal{I}]), \psi_2 = (R_3[\mathcal{H}, \mathcal{I}] \subseteq R_2[\mathcal{G}, \mathcal{I}], (x[\mathcal{I}]).$

The heuristic mentioned above works as follows. Let $\text{var}[A] = \{v_{\text{var}}1, v_{\text{var}}2\}$ for $A \in \{E, F, G, H\}$. We start with $D$ that contains

<table>
<thead>
<tr>
<th>Algorithm RandomChecking</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input:</strong> A set $\Sigma$ of CINDs and CFDs over schema $\mathcal{R} = (R_1, \ldots, R_n)$</td>
</tr>
<tr>
<td><strong>Output:</strong> true if a database $D$ can be built s.t. $D \models \Sigma$; false otherwise</td>
</tr>
<tr>
<td>1. $D :=$ an instance of $\mathcal{R}$ that contains, for a randomly chosen schema $R_i \in \mathcal{R}$, a single-tuple instance of fresh variables from $\text{Var}$;</td>
</tr>
<tr>
<td>2. $k := 0$;</td>
</tr>
<tr>
<td>3. while $\text{Varat}(\psi) \neq \emptyset$ or $k &lt; K$ do</td>
</tr>
<tr>
<td>4. randomly choose $\psi \in \text{Varat}(\psi)$;</td>
</tr>
<tr>
<td>5. $\text{Varat}(\psi) := \text{Varat}(\psi) - {\psi}$; $k := k + 1$;</td>
</tr>
<tr>
<td>6. if chase($\psi(D), \Sigma$) is defined then</td>
</tr>
<tr>
<td>7. return true;</td>
</tr>
<tr>
<td>8. return false.</td>
</tr>
</tbody>
</table>

The heuristic concludes that $\Sigma$ is consistent. Indeed, since the domain of $F$ and $H$ are infinite, it is always possible to find a mapping from the variables to values in the respective domains such that they do not satisfy the left pattern of any CIND and CFD. For example, by mapping $\text{var}[A] = d$ and $\text{var}[A] = e$, we obtain a database instance of $\mathcal{R}$ that satisfies $\Sigma$.

In contrast, if $\Sigma$ involves attributes with finite domains, we can no longer use chase($D, \Sigma$) as above, as shown by the next example.

Example 5.2: Consider $\Sigma$ of Example 5.1. If instead of having an infinite domain for $H$ we had dom($H$) = \{0, 1\}, then it is not always possible to find a valuation for the variables such that the result database of the chase w.r.t. the valuation satisfies $\Sigma$. For example, for $\psi_1 = 1$, we could still apply $\text{IND}(\psi_1)$. If, for example, there are also $\psi_1 = (R_1[\mathcal{E}, \mathcal{I}] \subseteq R_2[\mathcal{G}, \mathcal{I}], (x[I])$, and $\psi_2 = (R_1[\mathcal{H}, \mathcal{I}] \subseteq R_2[\mathcal{G}, \mathcal{I}], (b)[I])$, then $\text{IND}(\psi_2)$ would now apply, resulting in a database that does not satisfy $\Sigma$ because of $\psi_2$. |

Algorithm RandomChecking. To cope with finite domains, we develop an algorithm, called RandomChecking and given in Fig. 5.

While the chase given above always terminates, it may yield a witness database of exponential size. To avoid this, we adopt two further simplifications. (a) When applying $\text{IND}(\psi)$ for a $\psi \in \Sigma$, we need to add a new tuple that might have variables. If this variable is for an attribute with a finite domain, we modify $\text{IND}(\psi)$ in such a way that instead of adding a variable, a constant of the finite domain is used. (b) During the chase, if the number of tuples in any table exceeds a predefined threshold $T$, we say that the chase is undefined and terminate the process. The chase with these two simplifications is referred to as the "instantiated chase," and is denoted by chase($D, \Sigma$). More specifically, let $V'$ be the set of all variables associated with attributes that have finite domains. A valuation $\nu'$ w.r.t. $V'$ is a mapping from $V'$ to constants in the respective domains of the variables. We denote by $\nu(D)$ the database $D$ obtained by applying $\nu$ to $D$. Note that constants and variables with infinite domains in $D$ remain unchanged in $\nu(D)$. The set of all valuations $\nu'$ w.r.t. $D$ is denoted by $\text{Val}(\text{Var}(\mathcal{R}))$. If $\nu = 0$, then we assume that $\nu(D)$ consists of a single empty mapping.

Algorithm RandomChecking starts by creating a database $D$ that, for a randomly chosen relation $R \in \mathcal{R}$, contains a tuple $(v_1, \ldots, v_n)$ such that $v_i$ for attribute $A_i$ is a variable from $\text{Var}[A_i]$ (line 1). For a predefined parameter $K$, it then randomly picks up to $K$ valuations $\nu$ from $\text{Val}(\text{Var}(\mathcal{R}))$, and checks whether
Checking a chase sequence, chases with only true FDables with a finite domain that have not been assigned a value domain as described above. If a chase need to check the chase for mapping satisfying the constraints), the algorithm returns this, before applying a valuation.

While conceptually simple, it may hamper the chance of finding a witness database if we assign a value to variables with a finite domain before the chase starts. To rectify this, before applying a valuation $\rho$ from $\mathcal{V}_{instant}(\mathcal{R})$, we first chase with CFDs in $\Sigma$, which may instantiate certain variables by imposing constant bindings in their pattern tuples. This requires a procedure CFDChecking that, given a database $D_i$ (with variables) in a chase sequence, chases with only CFDs in $\Sigma$; that is, it applies $\text{FD}(\phi)$ for every CFD $\phi$ in $\Sigma$ that is applicable to $D_i$, instantiating variables in terms of constants in the pattern tuples when possible. The procedure applies $\rho$ from $\mathcal{V}_{instant}(\mathcal{R})$ only to the remaining variables with a finite domain that have not been assigned a value during the chase. Procedure CFDChecking returns a database $D_i+1$ in which all variables with finite domains have constant values, if $D_i$ is consistent with the CFDs in $\Sigma$, and it fails otherwise.

Capitalizing on CFDChecking, algorithm RandomChecking works as follows. It starts with chase$_i(D, \Sigma)$, and randomly picks a constraint in $\Sigma$ to chase with. Every time a new tuple is added to the database as a result of some $\text{IND}(\psi)$, it invokes procedure CFDChecking, which instantiates all variables with finite domains as described above. If CFDChecking fails, chase$_i(D, \Sigma)$ is undefined and the algorithm starts another random run. Eventually either chase$_i$ is defined in some run and thus RandomChecking returns true, or chase$_i(D, \Sigma)$ is undefined for all $K$ runs and the algorithm returns false. This is the algorithm we have implemented.

Procedure CFDChecking (not shown due to lack of space) can be implemented either as described above, or by leveraging existing tools for known NP problems, since the consistency problem for CFDs is in NP [9]. In the latter case, we reduce it to SAT, a well-known NP problem, and then check the consistency of the CFDs by using SAT4j [19], a well-developed tool.

5.3 Optimization: Dependency Graph Analysis

To further improve the accuracy and response time of our algorithms, we next present an optimization technique, based on a notion of dependency graphs of CFDs and CINDs. Below we first define dependency graphs. We then present a consistency checking algorithm that benefits from the usage of dependency graphs.

**Dependency graph.** For a set $\Sigma$ of CFDs and CINDs defined over a database schema $\mathcal{R}$, the dependency graph is defined as $\mathcal{G}[\Sigma] = (\mathcal{V}, \mathcal{E})$. The set $\mathcal{V}$ contains one vertex per relation $R_i$ in $\mathcal{R}$. Each vertex $R_i$ is associated with the set of CFDs defined on $R_i$ in $\Sigma$, denoted by CFD$(R_i)$, and a tuple template $\tau$, denoted by $\text{CFD}(\tau)$, which consists of distinct variables in each attribute of $R_i$. Later, $\tau$ will be instantiated to be a tuple that satisfies all the CFDs in CFD$(R_i)$ if CFD$(R_i)$ is consistent. The set $\mathcal{E}$ contains an edge from vertex $R_i$ to $R_j$ if there is at least one CIND from $R_i$ to $R_j$ in $\Sigma$. Furthermore, the edge is labeled with the set of all CINDs from $R_i$ to $R_j$, denoted by CIND$(R_i, R_j)$.

**Example 5.4:** Consider the following extension of the schema and constraints of Example 5.1: $\mathcal{R} = \{R_1, R_2, R_3, R_4, R_5\}$, CFD$(R_1) = \{E, F\}$, CFD$(R_3) = \{A, B\}$, CFD$(R_4) = \{C, D\}$, CIND$(R_1, R_3) = \{I, J\}$, and dom$(R_i)$ is bool. Also consider $\Sigma = \{\phi_1, \phi_2, \phi_3, \phi_4, \phi_5, \phi_6, \psi_1, \psi_2, \psi_3, \psi_4, \psi_5\}$, where $\phi_1\sim \phi_2$ and $\psi_1\sim \psi_2$ are those given in Example 5.1, and $\phi_3 = (R_3 : A \rightarrow B, (\varepsilon_{A,B}))$, $\phi_4 = (R_4 : C \rightarrow D, (\varepsilon_{C,D}))$, $\phi_5 = (R_5 : \text{null} \rightarrow \text{null}, (\varepsilon_{\text{null}}))$, $\psi_1 = (R_3[A; B])$, $\psi_2 = (R_3[A; B])$, $\psi_3 = (R_3[\text{null}; \text{null}], (\varepsilon_{\text{null}}))$, and $\psi_4 = (R_5[\text{null}; \text{null}], (\varepsilon_{\text{null}}))$. The graph $\mathcal{G}[\Sigma]$ is depicted in Fig. 6. Each node in $\mathcal{G}[\Sigma]$ is associated with a set of CFDs: CFD$(R_1) = \{\phi_1\}$, CFD$(R_2) = \{\phi_2\}$, CFD$(R_3) = \{\phi_3\}$, CFD$(R_4) = \{\phi_4, \phi_5\}$ and CFD$(R_5) = \{\phi_6\}$.

**Figure 6:** Graph $\mathcal{G}[\Sigma]$.

In a nutshell, we want to reduce $\mathcal{G}[\Sigma]$ by removing any node $R$ (and its related edges) for which CFD$(R)$ is inconsistent and thus has to be empty in any instance of $\mathcal{R}$ that satisfies $\Sigma$. The reduction is conducted with care such that it will not generate impact on the consistency analysis on the remaining graph. When the graph cannot be further reduced, it consists of strongly connected components such that if $\Sigma$ is consistent, then all relations in some of those components have to be empty. Furthermore, for each relation $R'$ in a component, CFD$(R')$ is consistent. This allows us to reduce the consistency analysis on $\mathcal{R}$ to the analysis on a single component. Better still, in some cases the graph reduction tells us whether or not $\Sigma$ is consistent. For example, if the final $\mathcal{G}[\Sigma]$ is empty then there is no relation $R$ for which CFD$(R)$ is consistent; as a result $\Sigma$ is inconsistent. On the other hand, we can conclude that $\Sigma$ is consistent if there is $R$ such that $\tau(R) = \text{CFD}(\tau)$ and the (instantiated) tuple $\tau(R)$ does not trigger any CIND in $\Sigma$, i.e., there is no CIND $R(X; X_\tau) \subseteq R'[Y; Y_\tau], t_\tau$ in $\Sigma$ such that $\tau(R)[X_\tau] \not= t_\tau[X_\tau]$. This is because a consistent instance of $\mathcal{R}$ can be built such that it consists of a $\{\tau(R)\}$ as the instance of $R$, and (b) empty instances for all other relation schemas.

We formalize this idea in algorithm preProcessing, shown in Fig. 7. First, the algorithm performs a topological sort on vertexes in $\mathcal{G}[\Sigma]$ (line 1) such that for any $R_i$ and $R_j$ in $\mathcal{G}[\Sigma]$ (a) if they are on a cycle, then an arbitrary order on $R_i$ and $R_j$ is adopted, and (b) otherwise, if there is edge from $R_i$ to $R_j$, then $R_i$ precedes $R_j$. The order is stored in a queue $Q$. Second, for each relation $R$ in $Q$, algorithm CFDChecking is called to check the consistency of CFD$(R)$ (lines 3-4). After running CFDChecking, if the set CFD$(R)$ is consistent, $\tau(R)$ becomes a tuple that satisfies CFD$(R)$, Furthermore.
Algorithm preProcessing

Input: The dependency graph \( G[\Sigma] \) of a set \( \Sigma \) of CINDs and CFDS.
Output: true if a database \( D \in \Sigma \) is found, the algorithm returns nil otherwise.

1. \( Q \leftarrow \) a topological order of nodes in \( G[\Sigma] \);
2. \( \text{while} \ Q \text{ is not empty do} \)
3. \( R \leftarrow Q.\text{dequeue}() \);
4. if CFDS Checking(CFD(R), \( \tau(R) \)) then
5. if \( \tau(R) \) does not trigger any CIND in \( \Sigma \) then
6. return 1;
7. else
8. for each \( R_j \) such that \( (R_j, R) \in E(G[\Sigma]) \)
9. add CIND \( (R_j, R) \) to CFD(R);
10. if \( R_j \) is not in \( Q \) then
11. \( Q.\text{enqueue}(R_j) \);
12. Delete node \( R \) from \( G[\Sigma] \);
13. Delete all nodes of \( G \) with indegree = 0;
14. if \( G[\Sigma] \) is empty then
15. return 0;
16. return -1;

Figure 7: Algorithm preProcessing

if \( \tau(R) \) does not trigger CIND in \( \Sigma \), then we can conclude that \( \Sigma \) is consistent, and return 1 (lines 5-6).

Now, if the set CFD(R) is inconsistent, we know that no database that satisfies \( \Sigma \) can have a nonempty \( R \). We can thus delete node \( R \) from \( G[\Sigma] \) after adding non-triggering CFDS to prevent all the neighboring relations from inserting tuples into \( R \) (lines 7-12). More specifically, for each \( R_j \) and each CIND \( (R_j, X_p \subseteq R[Y_p \cup t_p]) \) in \( \Sigma \), we add non-triggering CFDS \( (R_j : X_p \rightarrow A, \{t_p[X_p] \mid c_1 \}) \) and \( (R_j : X_p \rightarrow A, \{t_p[X_p] \mid c_2 \}) \), where \( A \in \text{attr}(R_j) \) and \( c_1, c_2 \) are distinct constants in dom(A). These two CFDS deny any tuple in \( R_j \) that matches the pattern \( X_p \). We use CIND \( (R_j, R)^+ \) to denote the set of all such non-triggering CFDS for \( R_j \) and its CINDs. If non-triggering CFDS are added to a node \( R_j \) for which CFD(Rj) was already checked for consistency, then \( R_j \) has to be added back to \( Q \) to make sure the updated CFD(Rj) is still consistent (line 11).

After checking the local consistency of CFDS for all nodes in \( G[\Sigma] \), the graph contains only relations for which the set of CFDS is consistent. If there is a node \( R \) that has no incoming edges, it can also be deleted (line 13), since we can make \( R \) empty without any impact on finding a consistent instance of \( \Sigma \). If after the process the graph is empty, we can conclude that \( \Sigma \) is inconsistent and return 0 (lines 14-15). Otherwise, whether or not \( \Sigma \) is consistent cannot be decided at this point, and thus -1 is returned.

Example 5.5: Continuing with Example 5.4, let \( G[\Sigma] \) be the graph of Fig. 6. Algorithm preProcessing starts by performing a topological sort. One possible output is \( Q = [R_a, R_b, R_1, R_2, R_3] \).

In the first while-iteration \( R = R_a \) and \( Q = [R_a, R_1, R_2, R_3] \).

Procedure CFDS Checking returns false since CFD(Ra) is \( \{\phi_a, \phi_b\} \). Procedure CFDS Checking returns true since CFD(R1) is consistent. Thus \( R_1 \) is deleted from \( G[\Sigma] \) after adding CFDS to \( R_3 \) in order to ensure that \( \psi_1 \) is not triggered. Now CFD(Rb) = \( \{\phi_b, (R_b : B \rightarrow A, \{b(c_1)\}), (R_b : B \rightarrow A, \{b(c_2)\})\} \). Since \( R_b \) is deleted from \( G[\Sigma] \), edge \( (R_b, R_3) \) no longer exists.

In the next iteration, \( R = R_3 \) and \( Q = [R_1, R_2, R_3] \). Procedure CFDS Checking returns true since CFD(R3), including the non-triggering constraints added in the previous step, is consistent. This means that since \( \psi_1 \) is not triggered, \( \tau(R_3) \) can be \( (v_1, v_2) \) where \( v_1 \) and \( v_2 \) are variables. This implies that \( \tau(R_3) \) does not trigger any CIND. This means that \( \tau(R_3) \) = \( \Sigma \) and that \( \Sigma \) is consistent.

Figure 8: Graph \( G[\Sigma] \) after preProcessing

Algorithm Checking

Input: A set \( \Sigma \) of CINDs and CFDS over schema \( R = (R_1, \ldots, R_n) \).
Output: true if a database \( D \) can be built s.t. \( D \models \Sigma \); false otherwise.

1. \( G \leftarrow \) the dependency graph \( G[\Sigma] \) of \( \Sigma \);
2. if preProcessing(G) = 1 then
3. return true;
4. if preProcessing(G) = 0 then
5. return false;
6. for each connected component \( G' \in G \)
7. Let \( \Sigma' \) be the CINDs and CFDS defined over \( G' \);
8. if RandomChecking(\( \Sigma' \)) then
9. return true;
10. return false;

At this point preProcessing returns 1.

As another example, let us replace \( \psi_1 \) in \( \Sigma \) by \( \psi'_1 = (R_3[A; nil] \subseteq R_3[C; nil], \{\phi_1\}). \) In the first while-iteration \( R = R_1 \) and \( Q = [R_1, R_3, R_2, R_3] \). The algorithm CFDS Checking returns false since CFD(R1) is consistent. Thus \( R_4 \) is deleted from \( G[\Sigma] \) after adding CFDS to \( R_3 \) in order to ensure that \( \psi'_1 \) is not triggered. Since \( X_p \) in \( \psi'_1 \) is nil, there is no way to avoid triggering it. This implies that \( R_3 \) also has to be empty. This is enforced by adding non-triggering CFDS, and now CFD(R1) = \( \{\phi_1, (R_1 : B \rightarrow A, \{c(c_1)\}), (R_1 : B \rightarrow A, \{c(c_2)\})\} \). These non-triggering CFDS are now inconsistent, and therefore no tuple will be added to \( R_3 \).

In the next iteration, \( R = R_3 \) and \( Q = [R_1, R_2, R_3] \). Procedure CFDS Checking returns false since CFD(R3), including the non-triggering constraints added in the previous step, is inconsistent. Node \( R_3 \) is therefore deleted from \( G[\Sigma] \).

Now, \( R = R_1 \) and \( Q = [R_1, R_2] \). Procedure CFDS Checking returns true since CFD(R1) is consistent. The CIND \( \psi_1 \) is triggered by any tuple in \( R_1 \) so we need to continue to the next relation. Subsequently, for \( R = R_2 \) and then for \( R = R_3 \), procedure CFDS Checking returns true and it is not possible to avoid the triggering of constraints. The queue is now empty and \( G[\Sigma] \) is reduced to relations \( R_1, R_2 \) and their edges.

The execution of line 13 of the algorithm will delete node \( R_3 \), since any database that contains tuples in \( R_3 \) and satisfies \( \Sigma \) can be replaced by another database that also satisfies \( \Sigma \) but without \( R_3 \).

When preProcessing terminates, \( G[\Sigma] \) is reduced to the graph shown in Fig. 8, and -1 is returned.

Algorithm Checking. We combine algorithm preProcessing with RandomChecking and develop algorithm Checking shown in Fig. 9. Initially, graph \( G[\Sigma] \) is constructed and pre-processed (lines 1-2). If preProcessing returns 1, from the discussion above we know that \( \Sigma \) is consistent and thus Checking returns true (lines 2-3). Similarly, if preProcessing returns 0, Checking returns false (lines 4-5). Otherwise preProcessing does not have an affirmative Boolean answer; it returns \( \varphi' \), a reduced version of \( G[\Sigma] \) that consists of only strongly connected components. Subsequently, Checking takes each connected component of \( \varphi' \) and calls RandomChecking that attempts to find the witness database \( D \) that satisfies \( \varphi' \) (line 6-8). If this database is found, the algorithm returns true (line 9). If for each connected component it cannot find such database \( D \), algorithm Checking returns false (line 10).
Example 5.6: Consider the set $\Sigma$ given in Example 5.4, with $\psi_i$ of Example 5.5 in place of $\psi_4$. If algorithm Checking is run to check the consistency of $\Sigma$, it would first call algorithm preProcessing which would return the reduced graph as shown in Fig. 8. The reduced graph has only one connect component with $R = \{R_1, R_2\}$ and $\Sigma = \{\varphi_1, \varphi_2, \psi_1, \psi_2, \psi_3\}$. Then, algorithm Checking runs RandomChecking (see Example 5.3).

It is easy to verify the correctness of our checking algorithms.

**Theorem 5.1:** Given a set $\Sigma$ of CINDs and CFDs, if either Checking or RandomChecking returns true, then $\Sigma$ is consistent.

For the complexity of the algorithms, given a schema $R$ and a set $\Sigma$ of constraints, let $n$ and $m$ be the numbers of CFDs and CINDs in $\Sigma$ respectively, $r$ be the number of relations, and $a$ be the maximum relation arity. Then, we have the following:

- (a) RandomChecking is in $O(a \cdot r \cdot (n^2 + m))$, (b) preProcessing is in $O(a \cdot r \cdot (n^2 + m^2) + r^2)$, and (c) Checking is in $O(a \cdot r \cdot (n + m)^2 + r^2)$. Note that in practice $a$ and $r$ will be much smaller than $n$ and $m$.

6. Experimental Study

We next present a preliminary experimental study of our heuristic methods for checking the consistency of CINDs and CFDs.

We compare the performance of our algorithms for checking the consistency of (a) CFDs alone, namely, the chase-based method and the method based on reduction to SAT presented in Section 5.2, for implementing CFDChecking, denoted by Chase and SAT, respectively, and (b) CFDs and CINDs put together, namely, RandomChecking and Checking. As shown by Theorem 3.2, there is no need to consider CINDs alone as they are always consistent.

For these algorithms we investigated their accuracy and scalability when varying both the schema (the number of relations) and the number of constraints. We use $F$ to denote the ratio of finite-domain attributes in the schema.

**Experimental setting.** We used relational schemas that include $\{R_1, R_2\}$ with $F$ ranging from 0% to 25%. Each finite domain was set to have 2 to 100 elements. The experiments show that $N$, the maximum size of $\text{var}[\Lambda]$, has a negligible impact on the accuracy of the algorithms. This is why we set $N = 2$ in the experiments, which makes the algorithms much more efficient.

We have implemented a generator that, given a schema $\mathcal{R}$, randomly generates sets of $\Sigma$ consisting of CFDs and CINDs defined over $\mathcal{R}$, with any given cardinality card($\Sigma$) of $\Sigma$. More specifically, each set $\Sigma$ was either consistent or inconsistent. We evaluated the accuracy of the algorithms by applying them on consistent and randomly generated sets of CFDs and CINDs. In order to generate the former, we took care to generate a consistent set $\Sigma$ of CFDs and CINDs by ensuring that there exists at least one possible value for each attribute so as to make a witness database of $\Sigma$.

The experiments were run on a machine with an Intel Pentium D 3.00GHz with 1GB of memory. Each experiment was run 6 times and the average is reported here.

**Experiments for CFDs only.** This experiment aimed at comparing the accuracy and scalability of Chase and SAT. In order to avoid the exponential cost of checking all the valuations of finite attributes in algorithm Chase, no more than $K_{CFD}$ valuations are allowed.

We varied the cardinality of card($\Sigma$) of $\Sigma$ while fixing the number of relations to 20, and $F$ to 25%. The results, given in Fig. 10(a), show that Chase significantly outperforms SAT in terms of scalability. Indeed, Chase works well even for a large number of CFDs. When the accuracy is concerned, Chase and SAT are comparable and both do very well: the percentage that they reported true when the input $\Sigma$ was consistent was 100% and only in a few occasions it was 95%. We also experimented with random sets of CFDs. In this case, the accuracy can be determined by running the algorithm with and without a limit $K_{CFD}$. Fig. 10(b) shows the results obtained for 1000 randomly generated CFDs while varying $K_{CFD}$ from 100 to 10K. In fact even when $K_{CFD}$ reaches 2000K, our algorithm still runs very fast. Thus we fixed $K_{CFD} = 2000K$ in the sequel.

Given the advantage of Chase over SAT, we adopted the chase implementation of CFDChecking in the rest of the experiments.

**Experiments for CFDs and CINDs.** Our second experiments evaluated the efficiency and accuracy of RandomChecking and Checking. We fixed the following parameters in these experiments:

1. **Schema:** $\mathcal{R}$ included 20 relations, with at most 15 attributes in each relation and $F$ ranging from 0% to 20%.
2. **Constraints:** $\Sigma$ consisted of 75% of CFDs and 25% of CINDs.
3. **Other Parameters:** $K$, the number of instantiation of finite domain attributes, is set to 20. $T$, the maximum number of tuples in each relation of the witness database, ranges between 2K and 4K.

Algorithms RandomChecking and Checking scaled well when the number of constraints was increased for both consistent and random set of constraints (see Fig. 11(b) and 11(c) respectively). Even though the running time of RandomChecking is theoretically better than Checking, in practice, most of the cases are solved in the preProcessing step and therefore Checking shows to be more efficient. Also, as shown in Fig. 11(a), for algorithms Checking the accuracy was almost constantly 100%. The experiments show that the preProcessing not only increases accuracy but it also improves the scalability of the algorithm. The high accuracy can be explained by the difficulty of generating consistent datasets that were complex enough for the algorithm to fail. However, we believe the datasets used in the experiments are already more complex than the ones found in practice.

To investigate the impact of the number of relations over the performance, the algorithms were run with different number of relations, but fixing the ratio of $|\Sigma|/|\mathcal{R}| = 1000$. The results of this experiment are given in Fig. 11(d).

**Summary.** We have presented preliminary results from our experimental study. First, we find that our heuristic methods, in almost all cases, accurately determine the consistency of CFDs and CINDs. Second, all algorithms, except SAT, scale well when the number of constraints or the size of relations increases. Third, we also find that the preProcessing optimization technique not only improves the accuracy, but also reduces the running time.

7. Related work

Closest to our work is the recent study of CFDs [9], which proposed the notion of CFDs, established the intractability of the consistency and implication problems for CFDs, and provided an SQL technique for finding CFD violations. However, neither CINDs nor their static analyses were studied in [9].

Also relevant are dependencies of [4, 21, 22] developed for constraint databases. Constrained dependencies of [21] are of the form $\xi \rightarrow (Z \rightarrow W)$, where $\xi$ is an arbitrary constraint that is not necessarily an FD. These dependencies apply FD $Z \rightarrow W$ only to the subset of a relation that satisfies $\xi$. They cannot express CFDs since $Z \rightarrow W$ does not allow patterns with constants as found in CFDs. More expressive are constraint-generating dependencies (CGDs) of [4] and constrained tuple-generating dependencies (CTGDs) of [22], of the form $\forall \exists (R_1(\bar{x}) \land \ldots \land R_k(\bar{x}) \land \xi(\bar{x} \rightarrow \xi'(\bar{y}))$ and $\forall \exists (R_1(\bar{x}) \land \ldots \land R_s(\bar{x}) \land \xi \rightarrow \exists\gamma[R_1'(\bar{x}, y) \land \ldots \land R_k'(\bar{x}, y) \land \xi'(\bar{x}, y)]$, respectively, where $R_1, R_1', R_2, \ldots$ are relation symbols, and $\xi, \xi'$ are arbitrary constraints. While both CGDs and CTGDs can express CFDs, and CTGDs can express CINDs, little is known about the complexity of their satisfiability and implication
Figure 10: Scalability and accuracy of consistency checking for CFDs and CINDs

Figure 11: Scalability and accuracy of consistency checking for CFDs and CINDs

problems, effective algorithms to solve these problems, or their inference systems. Indeed, for CGDs, the complexity of these problems is an open issue in the presence of constants or finite-domain attributes, even when \( \xi \) and \( \xi' \) are \((=, \neq)\) constraints; for CTGDs the satisfiability and implication problems are already undecidable even in the absence of \( \xi, \xi' \) and constants. That is, the expressive power of these dependencies comes with the price of high complexity. None of the prior results applies to CFDs or CINDs.

Constraints used in schema matching are typically standard INDs and keys (see, e.g., [16]). Contextual schema matching [7] investigated the applications of contextual foreign keys, a primitive and special case of CINDs, in deriving schema mapping from schema matches. While [7] partly motivated this work, it neither formalized the notion of CINDs nor considered static analyses of CINDs.

Research on constraint-based data cleaning has mostly focused on two topics [2]: repairing is to find another database that is consistent and minimally differs from the original database (e.g., [8, 13, 15]); and consistent query answering is to find an answer to a given query in every repair of the original database (e.g., [2, 25]). A variety of constraint formalisms have been used in data cleaning, ranging from standard FDs and INDs [2, 8, 13], denial constraints (full dependencies) [20], to logic programs (see [6] for a recent survey). To our knowledge, no prior work has considered pattern tableaux, which, as shown in [9], can be treated as data tables in SQL queries and thus allow efficient SQL techniques to detect constraint violations. Moreover, previous work on data cleaning did not study the consistency and implication problems of constraints, which are the focus of this paper.

As remarked earlier, algorithms and inference systems for the implication problems of standard FDs and INDs can be found in most database textbooks, and have also been well studied for a variety of constraints such as TGDS, equality generating dependencies.
and embedded dependencies (see e.g., [1]). In contrast to CFDs and CINDs, these constraints were studied in the absence of constant values (and negation), and thus their consistency analysis is trivial.

The consistency problem, a.k.a. the constraint satisfiability problem, has been studied for first-order logic constraints, for which heuristic methods have also been developed (see, e.g., [10, 23]). Unfortunately, attributes with finite domains were not considered in that context, and thus those algorithms cannot be applied to CINDs and CFDs. Methods have also been developed for the satisfiability problem for, e.g., description logics (see, e.g., [3]), in which CINDs and CFDs are not expressible.

The chase is widely used in implication analysis and query optimization, and has been studied for a variety of dependencies (see, e.g., [1]). Recently it was extended for query reformulation and schema mapping, and a number of sufficient conditions were identified to guarantee its termination (see [14] for a recent survey).

A heuristic method for chasing with FDs and INDs was proposed in [17], with the following simplifications to ensure termination: a predefined constant \( n \) times and then only one extra variable is allowed to be used to instantiate attributes of the tuples newly inserted when chasing INDs. This is, in spirit, similar to our predefined variable sets.

8. Conclusion

We have proposed CINDs, a mild extension of INDs that is important in both contextual schema matching and data cleaning. We have provided complexity bounds and a sound and complete inference system for consistency and implication problems of CINDs. We also established complexity bounds for reasoning about CINDs together with CFDs. These results settle the fundamental problems associated with conditional dependencies. Even if we consider only finite databases, i.e., databases where each relation has a finite extension, all the obtained complexity bounds still hold. It is left for future work in checking better complexity results can be obtained by considering extra assumptions, such as acyclicity of CINDs or CINDs with only unary relations.

In response to the intractability of the interaction between CFDs and CINDs, we have developed efficient heuristic algorithms for checking the consistency of CINDs and CFDs. As verified by our preliminary experimental results, these algorithms are promising for employing CINDs and CFDs in practical data cleaning and schema matching tools.

There is naturally much more to be done. In practice one often needs to find a minimal cover of a given set \( \Sigma \) of constraints, namely, a set \( \Sigma_{mc} \) that is equivalent to \( \Sigma \) but contains no redundancy. The computation of \( \Sigma_{mc} \) involves implication analysis, which is undecidable for CINDs and CFDs. Thus it is practical to develop heuristic algorithms for checking implication of CFDs and CINDs. Another interesting topic is propagation of CFDs and CINDs through SQL views. This is needed when deriving schema mapping from the constraints [16]. We are also investigating SQL-based techniques for detecting CIND violations in real-life data along the same line as [9] for data cleaning. Finally, effective use of CINDs and CFDs in schema matching and data cleaning requires a full treatment.

Acknowledgments. Wenfei Fan is supported in part by EPSRC GR/S63205/01, GR/T27433/01, EP/E029213/1 and BBSRC BB/D006473/1.

9. References