Tackling Polytype Queries in Inconsistent Databases: Theory and Algorithm

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Abstract—To expand query types under a set of integrity constraints for obtaining consistent answers over inconsistent databases, a computational theory is proposed based on first-order logic. According to directed join graphs of queries and their join completeness, computational complexities of CQA are PTIME if query types are key-key, nonkey-key, incomplete key-key with acyclic join. This paper presents several algorithms to tackle a large and practical class of queries, which can obtain the rewritten queries for computing consistent answers. For a rewritable initial query, a consistent identification statement is constructed based on the join graph by recursive computation; and the statement combines with the initial query to construct a new first-order rewritten query for computing consistent answers. To acyclic self-join queries, the recursive rewriting algorithm cannot eliminate inconsistent tuples, so the initial query combines with the statement that eliminates them.

Index Terms—relational database, inconsistent data; consistent query answer, first-order logic, query rewriting

I. INTRODUCTION

Integrity constraints (ICs) effectively enable data consistency and validity to conform to the rules of entities in the real-world. The current commercial DBMSes focus on a series of ICs to ensure every database is consistent. However, an entity of the real world frequently corresponds to inconsistent data w.r.t a given set of ICs while data are integrated from different data sources[1-2]. For example, a supplier $S$ has two conflict balances: 10 and 50. Give a query for returning suppliers whose balance is more than 20. A common query should return $S$. However, since the balance of $S$ may be 10, so the query result is incorrect.

It is difficult to repair the database in order to restore consistency. The process may be too expensive, and useful data may be lost. One strategy for managing inconsistent databases is data cleaning[3], which identifies and corrects data errors. However, these techniques are semi-automatic and infeasible for some applications such as a user wants to adopt different cleaning strategies or need to retain all inconsistent data. The trend toward autonomous computing is making the need to manage inconsistent data more acute. As a result, a static approach w.r.t a fixed set of constraints may not be appropriate.

An alternative approach is to employ CQA[1] to resolve inconsistencies at query time. CQA is the problem of retrieving “consistent” answers over inconsistent databases w.r.t a set of ICs. A first-order query rewriting algorithm[1] only employs conjunctive queries and binary constraints without quantifiers, some tractable queries could not be treated by query rewriting.

Conjunctive queries with quantifiers are based on join graph[4]. Every relation in the query is denoted as a node, an arc from a node to another node if an existential shared variable occurs in a non-key position in a node and occurs also in a key position in another node. Query classes have not repeated relation symbols, and every join condition involves the entire key of at least one relation[5,6]; they address first-order expressibility of acyclic queries without self-join in which no relation name occurs more than once. Since cycles are rare in queries, acyclic queries are very common. Most of queries arising in practice are in the class. In fact, 20 out of 22 queries in the TPC-H decision support benchmark[7] are in the class. As a further result, a dichotomy for a subclass of the class is following: the problem of computing the consistent answers is NP-COMPLETE for not every query in that class whose join graph is a forest[4].

Ref. [8] presents a query answering process based on conflict graph for dealing with denial constraints. It constitutes a compact, space-efficient representation of all repairs of a given database instance, the repairs correspond to maximal independent sets of the graph; vertices of the conflict graph are tuples in the database, an edge connects two vertices if they violate together an IC. Ref. [9] can handle arbitrary relational calculus queries and binary universal constraints. There is a one-to-one correspondence between database repairs and stable

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models of the logic programs. This approach can handle all first-order queries and a much wider class of ICs than the query rewriting technique. However, in the presence of one Functional dependency (FD) there may be exponentially repairs, the two methods are impractical to compute consistent answers of the bigger database efficiently.

To our best knowledge, no prior work has studied in the context of join completeness of polytype queries over inconsistent databases. Our main works are the following:

(a) This paper proposes the inconsistent data management theory based on the first-order logic and the directed join graph for identifying intractable and tractable queries by analyzing join completeness of polytype queries. Computational complexities of CQA directed join graph for identifying intractable and non-key-key, incomplete-key-key and their join graphs are acyclic correspond to queries.

(b) This paper presents several query rewriting algorithms for a large number of practical tractable queries, it first judges whether the queries are rewritable, a rewritable query will be constructed as a new rewritten query, then presents the query rewriting algorithm by recursive computation for subnodes according to the join graph.

II. THEORY

A. First-Order Logic

First-order logic supports a uniform language, which connects various signs to denote a logic deduction as constraints according to certain syntaxes[2]. CQA concentrates on relational databases. A fixed relational schema $S = (U, R, B)$ determines a first-order predicate logic $L(S)$, where $U$ is an infinite database domain, $R$ is a set of database predicates, and $B$ is a set of built-in predicates. Database instances are first-order structures over $L(S)$. We assume relation symbols by $S_1, \ldots, S_n$, tuples of variables and constants by $x, y, \ldots$, atomic formulas by $A_1, \ldots, A_n$, and quantifier-free formulas by $v$ (contain only built-in predicates). Basic classes of ICSs are the following:

(a) Universal IC: $\forall A_1 \land \cdots \land A_n \land v$ (binary if $n=2$);
(b) Denial constraint: $\forall \neg A_1 \land \cdots \land \neg A_n \land v$;
(c) FD: $\forall \exists x, y, y' : (\neg S(x, y) \lor \neg S(x, y')) \land y = y'$.

III. REPAIR

Definition 1. Inconsistent database (IDB) [1]. Given an instance $I$ of a database schema $R$ and a set of ICs $I'$, we say that $I$ is consistent if $I \models I'$. We can define true being a consistent answer to a Boolean query in a similar way.

Example 1. Suppose that a relation schema $R$ $(name, age)$, and an inconsistent instance $I = \{ (R(Tom, 20)), (R(Mary, 30)) \}$. There are two repairs: $I_1 = \{ (R(Tom, 20)), (R(Mary, 30)) \}$ and $I_2 = \{ (R(Tom, 25)), (R(Mary, 30)) \}$. All repairs have a minimal distance to $I$, $(R(Tom, 25))$, and $(R(Mary, 30))$ are not repairs because their distances w.r.t $I$ is not minimal under set inclusion. The minimality condition for the repairs is crucial in the definition. Otherwise, the empty set would trivially be a repair of every instance. For example, let $q_e = \exists age: (R(name, age))$. The consistent repairs for $q_e$ on $I_1$ are the tuples $(Tom)$ and $(Mary)$. Let $q_2 = \langle name, age \rangle = R(name, age)$. The only consistent answer for $q_2$ on $I$ is $(Mary, 30)$. Notice that the tuples $(Tom, 20)$ and $(Tom, 25)$ are not consistent answers. The reason is that neither of them is present in both repairs.

In fact, it is easy to see that there may be exponentially many repairs in the size of the database. Ideally, querying the given inconsistent databases should obtain consistent answers by, avoiding the explicit computation of repairs and filtering candidate answers. The input to the CQA problem is: a schema $R$, a set of ICs $I'$, and a database instance $I$ over $R$, $I$ might violate IC $I'$. A repair $I'$ of $I$ is an instance of $R$ such that $I'$ satisfies $\Sigma$, and $I'$ differs minimally from $I$. A tuple $i$ is said to be a consistent answer for a query $q$ on $I$ if $I' \models q(i)$, for every repair $I'$ of $I$.

Under this definition, repairs need not be unique.
Intuitively, each repair may be a possible consistent database.

C. Directed Join Graph

In order to define such conditions precisely, we will state them in terms of what we call the directed join graph of the query. In the graph, nodes express relations of the query, arcs express attributes of the query.

Definition 5. Let $Q$ be a SPJ query, $R_1$ and $R_2$ are two relations in $Q$. The graph $G$ of $Q$ is a directed join graph, if $G$ meets a certain following conditions, we say that the query is polytype. (a)the vertices of $G$ are the relations used in $Q$; (b)all joins involve the key of at least one relation; (c)there is an arc from $R_i$ to $R_j$ if an attribute of $R_i$ is equated with the key attribute of $R_j$; (d)$G$ is a tree; (e)a relation appears in the FROM clause at most once; (f)the key of the relation at the root of $G$ appears in the SELECT clause.

The first condition expresses that every relation is used at most once in a query. The second one expresses that every join involves the key of at least one relation. The third one expresses that a non-key attribute of a relation is equated with a key attribute of another one. The fourth condition expresses that self-join does not exist. The fifth condition expresses that a key of a relation joins non-key attributes of the other two relations do not exist.

The most form of joins is from a non-key attribute of a relation to the key of another one. Furthermore, such joins typically involve the primary key of the relation. Finally, cycles are rarely present in the queries used in practice, which do not have repeated relation symbols.

If $Q$ is a conjunctive query and its join graph is directed, $Q$ is rewritable. We divide queries into several types as the following:

$q_1 = x_1 . y_1$. $R_1(x_1, y_1) \land R_2(x_1, y_1)$ is a nonkey-nonkey join;

$q_2 = x_1 . y_1 . z_1 . w_1. R_1(x_1, y_1) \land R_2(z_1, w_1) \land R_3(z_1, y_1)$ is a nonkey-key join, and the number of nodes with in-degree 0 is 2, so it is not a root tree;

$q_3 = x_1 . y_1 . z_1 . R_1(x_1, y_1) \land R_2(z_1, x_1)$, $q_3$ is a nonkey-key join with a cyclic, and the join of $x$ over the key attribute of $R_1$ is not complete;

$q_4 = x_1 . y_1 . z_1 . R_1(x_1, y_1) \land R_2(x_1, z_1)$ is a nonkey-key join with a cyclic between repeated relations;

$q_5 = x_1 . y_1 . z_1 . R_1(x_1, y_1) \land R_2(x_1, z_1) \land R_3(z_1, w_1) \land R_4(z_1, c)$ is a nonkey-key join.

Figure 1. Directed join graphs

D. Intractable Query

Definition 6. Assume a conjunctive query $Q: R_1(x_1, y_1)$ and $R_2(x_2, y_2)$, if every variable of $x_1$ appear in $y_1$ or $x_2$, the join is complete; if every variable of $y_2$ does not appear in $y_1$ or $x_2$, the join is not complete.

We don’t present a kind of query: every variable of $x_j$ does not appear in $x_i$ ($i = j$), the type of query is impossible.

Theorem 1. Assume a conjunctive query $Q: R_1(x_1, y_1)$ and $R_2(x_2, y_2)$, if every variable of $x_j$ does not appear in $x_i$ ($i = j$), the type of query is impossible.

Proof: Assume the type of query is possible, the number of attributes of $x_j$ is less than $x_i$. Since $i = j$, $x_i = x_j$, the number of attributes of $x_j$ is equal to $x_i$. Contradiction.

Theorem 2. To a given conjunctive query with multi-relations and key constraints, if its join types are nonkey-nonkey, computing CQA is NP-COMPLETE problem.

However, the type of conjunctive queries based on key constraint is nonkey-nonkey with single relation, it generates cycles in its join graph. The type of queries does not belong to $C_{rew}$ type[6]. To $C_{rew}$ type, if relax join constraints (e.g., nonkey-key join is not complete), this raises NP-COMPLETE problem. To the type of computable conjunctive queries, iff join graphs of conjunctive queries are not cyclic. However, a large number of practical conjunctive queries are rewritable for first-order logic, computing their CQA are tractable. We should prove that nonkey-nonkey joins with multi-relations are also NP-COMPLETE problem.

Theorem 3. To a given conjunctive query with multi-relations and key constraints, if its join types are nonkey-nonkey, computing CQA is NP-COMPLETE problem.

Proof: This proof may simplify by MONOTONE 3-SAT. Set $\beta = \delta_1 \wedge \ldots \wedge \delta_m \wedge \psi_1 \wedge \ldots \wedge \psi_p$ be a conjunctive query, $\delta_i$ is positive, $\psi_i$ is negative. Assume two binary relations $R_1$ and $R_2$, the first attribute of the relation is the key attribute. We create an instance $I$, if variable $\nu$ appears in $\delta_i$, $I(R_1)$ includes tuple $(i, \nu)$; if variable $\nu$ appears in $\psi_i$, $I(R_2)$ includes tuple($\nu$); so $Q \equiv \exists x, y, z: R_1(x, y) \land R_2(y, z)$. Iff exist a repair of I as $I^+ 
 \neq Q$, which is satisfied with $\beta$.

Theorem 4. To a given conjunctive queries with multi-relations and key constraint, if its join types are nonkey-nonkey and their join graphs exist cycles, computing CQA is NP-COMPLETE problem.

Proof: This proof may simplify by MONOTONE 3-SAT. Set $\beta = \delta_1 \wedge \ldots \wedge \delta_m \wedge \psi_1 \wedge \ldots \wedge \psi_p$ be a conjunctive query, $\delta_i$ is positive, $\psi_i$ is negative. Assume two binary relations $R_1$ and $R_2$, the first attribute of the relation is the key attribute. We create an instance $I$, if variable $\nu$ appears in $\delta_i$, $I(R_1)$ includes tuple $(i, \nu)$; if variable $\nu$ appears in $\psi_i$, $I(R_2)$ includes tuple($\nu$); so $Q \equiv \exists x, y: R_1(x, y) \land R_2(y, x)$. Iff exist a REPAIR of I as $I^+ \neq Q$, which is satisfied with $\beta$. 

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Theorem 5\textsuperscript{(10)}. Assume two queries $Q: \exists x,y,m,z: R1(x,y) \land R2(m,y,z)$ and $Q^*: \exists x',y: R1(x,y) \land R2(x',y)$. It is a PTIME reduction from $Q^*$ to $Q$ for computing, so it is a PTIME reduction from join among part key attributes to join among nonkeys for computing CQA.

Theorem 6. To a given conjunctive query and key constraints, if its nonkey-key join types are not complete, computing CQA is NP-COMPLETE problem.

Proof. According to Theorem 5, it is a PTIME reduction from join among part key attributes to join among nonkeys for computing CQA, so it is a PTIME reduction from join with nonkey-nonkey attributes to incomplete join with nonkey-key for computing CQA. Since the nonkey-nonkey join for computing CQA is NP-COMPLETE problem, the nonkey-key join for computing CQA is NP-COMPLETE problem.

Theorem 7. To a given conjunctive query and key constraints, if its key-key join types without repeated relations are complete incomplete, computing CQA is NP-COMPLETE problem.

Proof. According to Theorem 5, it is a PTIME reduction from join among part key attributes to join among nonkeys for computing CQA, so it is a PTIME reduction from join with nonkey-nonkey attributes to incomplete join with key-key for computing CQA. Since the nonkey-nonkey join for computing CQA is NP-COMPLETE problem, the incomplete join with nonkey-key for computing CQA is NP-COMPLETE problem.

E. Tractable Query

Theorem 8\textsuperscript{(10)}. To a given conjunctive query and key constraints, if its joins are key-key or its nonkey-key joins are complete while the join graphs corresponds to queries are not cyclic, computing CQA is NP-COMPLETE problem.

Theorem 9. To a given conjunctive query and key constraints, if its key-key joins are not complete, computing CQA is PTIME.

Proof. According to Theorem 5, it is a PTIME reduction from join among part key attributes to join among nonkeys for computing CQA, so it is a PTIME reduction from join with nonkey-nonkey attributes to incomplete join with key-key for computing CQA. According to Theorem 8, computing CQA for nonkey-key is PTIME, so computing CQA for incomplete join with key-key is PTIME.

According to Theorem 8 and Theorem 9, computing CQA for $q_5$, $q_6$ and $q_7$ are PTIME. According to Theorem 2, Theorem 3, Theorem 4, Theorem 6 and Theorem 7, computing CQA for $q_9$, $q_{10}$ and $q_{11}$ are NP-COMPLETE problem.

The second query exists a nonkey-key join, but it has two nodes whose in-degrees are 0. In fact, the join between $R_1$ and $R_2$ is nonkey-nonkey join, these nodes are greater than 1 while their in-degrees are 0, the nonkey-key join is a subclass of common nonkey-nonkey joins. As a result, we classify three types as nonkey-nonkey joins such as the nonkey-key join whose nodes are greater than 1 while their in-degrees are 0, the incomplete nonkey-key join and the complete incomplete key-key join. According to this class, $q_1$, $q_2$ and $q_3$ are the nonkey-nonkey join.

A great number of intractable query types exist, but these intractable queries are rarely exist. Since cycles rarely appear in practical queries, $q_{13}$ is prevailing. More queries join between a nonkey attribute of a relation and a key attribute of another one, the join with nonkey-key is complete.

Query rewriting employs first-order rewriting method to rewrite a great number of tractable queries, rewritten queries are also first-order, they may be expressed by SQL. An original query and its rewritten query are same type, computing CQA can be reused by same database query engine, this economizes functions of current DBMSes and need not preprocessing and reprocessing of procedures. Since rewritten queries should be obtained by PTIME way with independent data, the method is PTIME on computation complexity.

Definition 7. Assume $R$ is a schema, $IC$ is a set of ICs, $q$ is a query over $R$. To every instance $I$ of $R$, $IC$, if a query $Q$ exist and $I[Q(t) \equiv t \in CQA(q,I,IC)]$, $Q$ is a first-order query w.r.t. $I$ and $IC$.

To a given query, we firstly identify whether the query is computable, and select a relevant algorithm according to the query type to compute CQA. To several tractable queries, we divide them into two types: key-key join query and nonkey-key join query, and present relevant algorithms.

Example 2. In a relation $R(x,y)$, assume a query $q = \exists x: R(x,10)$ and an instance $I_1 = \{(v,1), (v,5)\}$, repairs are $I_2 = \{(v,10)\}$ and $I_3 = \{(v,5)\}$, though $I_1 \not\models q$, $I_3 \models q$. In an instance $I_4 = \{(v,1), (v,5), (v,2), (10)\}$, repairs are $I_5 = \{(v,10), (v,2)\}$ and $I_6 = \{(v,5), (v,2), (10)\}$. As a result, $I_4 \not\models q$.

We may employ $\forall y: (R(x,y) \rightarrow y)$ to indentify consistency for $y=10$, this should obtain the following sentence:

$$Q = \exists x: R(x,10) \land \forall y: R(x,y) \rightarrow y = 10.$$

Obviously, assume a query $q' = \exists x: R(x,y)$, its rewritten query is the following:

$$Q' = \exists x: R(x,y) \land \forall y*: R(x,y*) \rightarrow y = y*.$$

where, $y*$ is a possible value.

Above queries are not joined, the following sentences should consider nonkey-key join queries.

Example 3. In a relation $R(x,y)$, assume a query $q = \exists x,y,w: R(x,y) \land R(x,w)$ in an instance $I_1 = \{(R(v,a), R(v,a), R(a,b))\}$, repairs are $I_2 = \{(R(v,a), R(a,b))\}$ and $I_3 = \{(R(v,a), R(a,b))\}$, though $I_1 \not\models q$, $I_3 \not\models q$. In an instance $I_4 = \{(R(v,a), R(v,a), R(a,b))\}$, all nonkey values $(a1$ and $a2)$ of $v1$ in $R1$ appear in $R2$. As a result, $I_4 \not\models q$.

This may employ a sentence $\forall y: (R(x,y) \rightarrow \exists w: R(y,w))$ to check, the rewritten query is a conjunction about the sentence and original sentence.
\[ Q = \exists x, y, w: R_1(x, y) \land R_2(y, w) \land \forall y: (R_4(x, y) \rightarrow \exists w: R_3(y, w)). \]

III. ALGORITHM

A. Identifying Rewritable Query

Now we present several algorithms for treating rewritable queries. The first algorithm identifies whether queries are tractable, the second one presents the query rewriting method. Since our method is based on the join graph, the third algorithm considers recursive computation for subnodes. Since the number of relations is limited and computation without data, the following algorithms are simple on computation complexity.

**Algorithm 1. judge-rewritable(q, IC)**

**INPUT:** a query \( q(v) : \exists w: R_1(x, y) \land \ldots \land R_d(x, y), \) a set of key constraints IC

**OUTPUT:** whether the query is rewritable

**BEGIN**

1. \( G = \) the join graph of \( q; \)

2. \( R = \{R_1, \ldots, R_d\}; \)

3. **IF** \( n = 1 \) \{RETURN TRUE; END PROCEDURE;\}

4. FOR \( i = 1 \) TO \( m - 1 \) DO

5. **IF** \( R[n] = R[i] \)

6. **IF** the join type of \( R[n] \) is nonkey-key with cyclic or nonkey-nonkey

7. **RETURN** FALSE; END PROCEDURE;\]

8. **ELSE** [RETURN TRUE; END PROCEDURE;]\}

9. **END** FOR

10. **END**

Figure 2. An algorithm for identifying rewritable queries.

Since queries without joins are not rewritable, algorithm 1 firstly identifies the number of relations in the input query \( q \) with built-in predicates \( v \) indicated as \( \exists w: R_1(x, y) \land \ldots \land R_d(x, y), x, y \) indicate a constant or a variable in the key and non-key position respectively, \( w \) is a variable, \( v \) is a free variable. If it is a query without join, the algorithm returns TRUE and ends the procedure. The algorithm compares set elements of relations to identify whether self-join exist, if self-join exist, its join type is nonkey-key with cyclic or nonkey-nonkey, the algorithm returns FALSE and ends the procedure; otherwise, the algorithm returns TRUE and ends the procedure. If the query is not self-join, its join type is nonkey-key with cyclic, nonkey-nonkey, incomplete nonkey-key and full incomplete key-key or nodes with in-degree 0 are greater than 1, the algorithm returns FALSE and ends the procedure; otherwise, the algorithm returns TRUE and ends the procedure.

B. Rewriting Algorithm

If a query is writable, we should employ the following algorithm to obtain a rewritten query.

Algorithm 2 firstly obtains join components and their root nodes of the join graph w.r.t the query by cyclicing according to the number of nodes. If the root node of a join component exist subnodes, we should obtain join components of the subnodes of the node. If the node is a tree root, we should obtain the node value w.r.t. the tree root

\[ q \land \exists y: R_1(x, y) \land \forall y: R_2(x, y) \rightarrow \text{recure}(Q); \text{recure}(Q) \]

should call a recursive algorithm (Fig. 4).

In “\( q \land \exists y: R_1(x, y) \land \forall y: R_2(x, y) \),” \( q \) is an original query and \( R_1(x, y) \) is a root node, conductional variables of existential quantifiers and universal quantifiers are nonkey attributes.

Algorithm 2. rewritten_query(q, IC)

**INPUT:** a query \( q(v) : \exists w: R_1(x, y) \land \ldots \land R_d(x, y), \) a set of key constraints IC

**OUTPUT:** a rewritten query

**BEGIN**

1. \( G = \) the join graph of \( q; \)

2. \( T_1, \ldots, T_m = \) the node component of \( G; \)

3. \( R_1(x, y) = \) the root node of \( T_i; \)

4. \( Q(v(x, y)) = \) NULL;

5. FOR \( i = 1 \) TO \( m \) DO

6. **IF** \( R_i(x, y) = \) a subnode of \( R_1(x, y) \)

7. \( \{Q = Q \land Q_i;\} \)

8. **END** IF

9. **END** FOR

10. **RETURN** \( Q \land \exists y: R_1(x, y) \land \forall y: R_2(x, y) \rightarrow \text{recure}(Q); \)

**END**

Figure 3. A query rewriting algorithm.

Algorithm 3 is a recursive algorithm, its input is query components, and its output is the rewritten query of the subnode. We firstly obtain the node and their subnodes that correspond to of query components. If the node is a leaf and nonkey attributes of the node, which exist the conductional variables of existential quantifiers. If the node is a leaf and nonkey attributes of the node, which exist the conductional variables of existential quantifiers. If the node is not a leaf, \( \exists y: R_1(x, y) \land \forall y: R_2(x, y) \rightarrow \text{recure}(q); \text{recure}(q) \) executes a recursive computation, conductional variables of existential quantifiers and universal quantifiers are nonkey attributes.

Algorithm 3. recure(q)

**INPUT:** a conjunctive query \( Q \land \ldots \)

**OUTPUT:** a rewritten query of a subnode

**BEGIN**

1. \( R_1(x, y) = \) the node that corresponds to of \( q; \)

2. \( R_2(x, y) = \) the subnode of the node that corresponds to of \( Q; \)

3. **IF** \( q = \text{NULL} \) and \( v = v \) \{if it is a leaf\}

4. \( \{Q = \exists y: R_1(x, y) \land \forall v': (R_2(x, y) \rightarrow v = v');\} \)

5. **RETURN** Q
This paper proposes an inconsistent data management theory based on the first-order logic and the directed join graph for identifying intractable and tractable queries by analyzing join completeness of polytype queries. To a great number of practical tractable conjunctive queries, we present several query rewriting algorithms to construct a new rewritten query by recursive computation according to the join graph w.r.t. an original query. The next work should consider more integrity types such as foreign key type.

IV. CONCLUSION

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