Automating semantics-based reconciliation for mobile transactions

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Abstract

Optimistic replication lets multiple users update local replicas of shared data independently. These replicas may diverge and must be reconciled. In this paper, we present a general-purpose reconciliation system for mobile transactions. The basic reconciliation engine treats reconciliation as an optimization problem. To direct the search, it relies on semantic information and user intents expressed as relations among mobile transactions. Unlike previous semantics-based reconciliation systems, our system includes a module that automatically infers semantic relations from the code of mobile transactions. Thus, it is possible to use semantics-based reconciliation without incurring the overhead of specifying the semantics of the data types or operations.

1. Introduction

Distributed systems replicate shared data to improve read availability and performance. Optimistic replication allows a user to *update* a local replica independently. This improves write availability in the presence of high network latencies, failures, voluntary disconnection, or parallel development, but allows replicas to diverge. This is especially useful for mobile computing environments.

Repairing divergence after the fact, called *reconciliation*, combines the isolated updates [16]. In operation-based (or log-based) approaches, update actions are recorded in a log; reconciliation *replays* the combined actions, from the initial state, according to some *schedule*.

Sometimes, it is impossible to execute all updates because the execution of some updates would violate a *precondition* or an *invariant*. In this case, relying on conflict resolution rules (e.g. exploring alternative updates) and running updates in a different order may allow better reconciliation results (i.e., more updates can be executed). The updates that cannot be executed must be *dropped*. Reconciliation must minimize the dropped updates, as dropping an action may have a high impact.

1.1. Limitations of existing systems

Several systems use optimistic replication and implement some form of reconciliation — see [16] for a recent survey. Many older systems reconcile by comparing final tentative states (e.g. Coda [8]). Other systems use history-based reconciliation (e.g. [18, 12, 10]). This is also our approach.
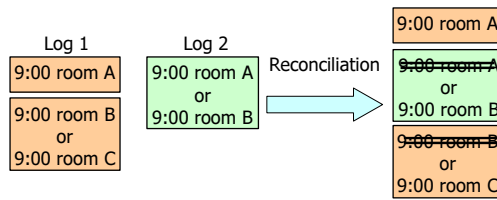

Figure 1: Syntactic scheduling spuriously fails on this example

Many existing reconciliation systems are dedicated to a single application semantics — e.g. CVS [2]. Others (e.g. Bayou [18] and Deno [7]) are general-purpose and use a simple syntactic criterion (e.g. timestamps) to decide which updates to retain and/or the order to run them. This is inflexible and may cause spurious conflicts even in very small problems. Consider the example of figure 1, where two users make meeting requests to a calendar program. One user requests room A at 9:00, and either room B or C, also at 9:00. Meanwhile, other user requests either room A or B at 9:00. Combining the logs in some simple way does not work. For instance running Log 1 then Log 2 will reserve rooms A and B for the first user, and the second user's request is dropped. Running Log 2 first has a similar problem. Satisfying all three requests requires reordering them, which syntactic systems cannot do.

Semantics-based reconciliation systems use semantic information to merge divergent streams of activity. Several approaches have been proposed. In [19], commutativity information is used to improve concurrency. In Sync [10], the programmers may define reconciliation rules for each pair of actions that can be executed upon each object. Operational transformation algorithms [17] re-write update parameters to enable order-independent execution of non-conflicting actions, even when they do not commute.

Experiments show that semantics-based reconciliation tends to produce better reconciliation results [15]. However, the overhead of expressing the semantic information needed by the reconciliation engine is usually non-trivial. Therefore, some programmers will not be willing to execute this extra work or end up creating bad semantic rules that lead to poor reconciliation results.

1.2. Our approach
This paper presents the SqlIceCube general-purpose reconciliation system for mobile database systems.

In SqlIceCube, update actions are expressed as small programs written in a subset of PL/SQL [11]. These programs, dubbed mobile transactions (or simply transactions), are submitted by users' applications to modify the database. Figure 2 presents a simple mobile transaction to submit a new order in a mobile sales application. The code of the transaction verifies if the stock is sufficient and the price is acceptable before adding the new order to the database.

Mobile transactions may be tentatively executed against local replicas. These mobile transactions are then submitted to the SqlIceCube reconciliation system that combines concurrently executed transactions. During reconciliation, the mobile transactions' programs are executed again (i.e., mobile transactions are not integrated in the database using the read sets/write sets of the tentative execution). Reconciliation is executed in two steps: the semantic inference and

```
----------------- ORDER PRODUCT: id = 80; quantity = 10; highest price = 100.00 --------------------
DECLARE
  l_stock INTEGER;
  l_price FLOAT;
BEGIN
  SELECT stock,price INTO l_stock,l_price FROM products WHERE id = 80;
  IF l_price <= 100.0 AND l_stock >= 10 THEN            -- check price acceptability and stock availability
    UPDATE products SET stock = stock - 10 WHERE id = 80;
    INSERT INTO orders VALUES (newid,8785,80,10,l_price,'to process');  -- newid returns the same unique
                                                         -- identifier in the client and in the server
    COMMIT;                                              -- commit transaction (and return)
  ELSE
    ROLLBACK;                                            -- abort transaction (and return)
  ENDIF;
END;
```

Figure 2: Mobile transaction adding a new order in a mobile sales application.

the basic reconciliation steps.

The semantic inference module automatically infers the semantic information needed by the basic reconciler. This information is obtained in two steps. First, each transaction is statically analyzed to extract relevant information (read/written data items and preconditions). Second, for each pair of transactions, a set of semantic static relations (e.g. commute) is inferred using the extracted information.

The basic reconciler treats reconciliation as an optimization problem, trying to find the schedule that allows more transactions to succeed. The static semantic information directs the search using an heuristic approach. This reconciler extends the IceCube reconciler detailed in [15].

The main contribution of this work is the semantic inference mechanism to simplify the use of semantics-based reconciliation. Unlike previous systems, semantic information used during reconciliation is automatically extracted from operations, thus alleviating programmers from most of the work usually involved in semantics-based reconciliation.

This work also identifies a set of static relations that can be automatically extracted to expose semantic information relevant for reconciliation problems. This information includes not only the semantics of the data types and operations but also the users' intents.

The remainder of this paper is organized as follows. Section 2 outlines the general-purpose semantics-based reconciler. Section 3 describes the semantic inference module. Section 4 discusses some extensions and on-going work and section 5 concludes the paper with some final remarks.

2. Generic semantics-based reconciler

In this section we outline the generic SqlIceCube reconciler. We start by describing the semantic information used.

2.1. Dynamic constraints/pre-conditions

Dynamic constraints are restrictions to the execution of a mobile transaction that depend on the database state. Therefore, they can only be verified at runtime. These restrictions are specified in the code of transactions as preconditions that lead to *commit* or *rollback* statements. For example, the transaction of figure 2 can only commit if the stock and price for the specified

product meet the given conditions. Whenever possible, we use this information to infer suitable static relations, as explained later.

2.2. Static constraints/relations

Static constraints are relations among mobile transactions that do not depend on the database state. Therefore, they can be used during the reconciliation process without accessing the database. Two types of static relations are used: log relations and data relations.

2.2.1. Static log contraints/relations

Log constraints are relations that express users' intents. These relations are independent of the semantics of each specific basic transaction. Instead, they encode the semantics of a macro-operation composed by several basic transactions. Usually they are explicitly set by applications but some of them can also be automatically inferred as discussed later. The following log relations are defined:

Alternatives Specify that a single transaction must be committed from a set of alternatives. This allows the definition of basic conflict resolution rules. For example, when scheduling a meeting, a user can specify two or more alternative meeting rooms or dates.

Strong predecessor-successor The successor transaction can only be executed after (and if) the predecessor transaction commits. This allows to establish a causal order between transactions. For example, a transaction that submits requests related to a given meeting (e.g. food for the coffee break) should only be executed after committing the transaction that schedules the meeting.

Weak predecessor-successor If both transactions commit, the predecessor must be executed before the successor. This allows to establish a weak causal order between transactions. For example, a transaction that schedules a new appointment for some day should be executed after executing the transaction that have previously cancelled all existent appointments for that day.

Parcel Defines an all-or-nothing group of transactions. Unlike the operations in a transaction, the execution of the basic transactions that compose a parcel may be interleaved with the execution of other transactions. Thus, the isolation property of transactions is not guaranteed in a parcel, although the execution of each basic transaction respects isolation. For example, a bank transfer can be defined as a parcel with two transactions, one withdrawing money from the source account and the other depositing money in the destination account.

2.2.2. Static data constraints/relations

Data constraints are relations between transactions that encode the semantics of the operations, independently of the database state. The following static data relations are used:

Commute Two transactions commute if the result of executing both is independent of the execution order, i.e., given two transactions t_1 and t_2, $\forall s \in \mathcal{S}, t_1(t_2(s)) = t_2(t_1(s))$, with $\mathcal{S}$ the set of all possible database states. For example, two transactions that modify unrelated data items commute.

Helps The transaction t_1 *helps* the transaction t_2 if the commitment of t_1 changes the database state in a favorable way for the success of t_2, i.e., $\exists s \in S : \neg valid(t_2,s) \wedge valid(t_2,t_1(s))$, with $valid(t,s)$ true if t can commit in database state s. For example, a transaction that raises the stock of some product improves the chance of accepting a new order request (with the available stock).

Makes possible The transaction t_1 *makes possible* the transaction t_2 if the commitment of t_1 changes the database state in a way that makes possible to commit t_2, i.e., $\forall s \in S, valid(t_2,t_1(s))$. Thus, while *helps* only favors the successful execution of the second transaction, *makes possible* is stronger and guarantees its success. For example, removing all meetings in a given room makes possible to schedule a new meeting for that room.

Prejudices The transaction t_1 *prejudices* the transaction t_2 if the commitment of t_1 changes the database state in a prejudicial way for the success of t_2, i.e., $\exists s \in S : valid(t_2,s) \wedge \neg valid(t_2,t_1(s))$. For example, a transaction that decreases the stock of some product hinders the chance of accepting a new order request.

Makes impossible The transaction t_1 *makes impossible* the transaction t_2 if the commitment of t_1 changes the database state in a way that makes impossible to commit t_2, i.e., $\forall s \in S, \neg valid(t_2,t_1(s))$. Thus, while *prejudices* makes more likely the impossibility of committing the second transaction, *makes impossible* guarantees this impossibility. For example, setting the price of some product to a value that violates the preconditions of an order request makes impossible to accept this request (while raising the price only makes it more likely to be impossible to accept the request).

The static relations *helps*, *prejudices*, *makes possible* and *makes impossible* encode the influence of one transaction over the dynamic constraints/preconditions of the other transaction.

2.3. Heuristic reconciliation engine

The goal of the reconciler is to create a schedule that maximizes the number (or value) of transactions that can be executed with success. As, for non-trivial problems, it is impossible to check all possible schedules, we have implemented a reconciliation algorithm that probes the space of possible solutions heuristically. To this end, the reconciler creates and executes a sequence of schedules that combine the transactions submitted concurrently by multiple mobile clients. The reconciliation process ends when a schedule that meets a specified optimality condition is generated (or the specified search time is exhausted).

The reconciler creates each schedule incrementally. At each step, the reconciler selects for execution one transaction based on its merit (with randomization). The merit heuristically computes the benefit of adding a given transaction to a given partial schedule. An oracle estimates the merit of each transaction based on the static relations established between this transaction and all other transactions that can still be scheduled. The merit of transaction t is:

1. Zero if t has a strong predecessor that has not been executed yet (i.e. dependencies are not satisfied) or t has an alternative that has already been executed (as a single alternative must be executed).

2. Inversely proportional to the total value of weak predecessors of t, as weak predecessors have to be aborted if t is selected.

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3. Inversely proportional to the total value of alternatives to t, as it is more likely to be possible to commit one transaction with more alternatives.

4. Inversely proportional to the total value of transactions t makes impossible, as those transactions cannot be committed, at least temporarily. Directly proportional to the total value of transactions t makes possible.

5. Directly proportional to the total value of weak and strong successors of t, as successors are made possible by the execution of the predecessor.

6. Directly proportional to the total value of transactions t helps, as those transactions are more likely to be successfully executed. Inversely proportional to the total value of transactions t prejudices.

The above factors are listed in decreasing order of importance. Due to space limitation it is impossible to further details our reconciliation engine. The SqlIceCube reconciliation algorithms and optimizations (e.g. clustering) are detailed elsewhere [14].

3. Automatic extraction of (data) relations

As explained before, the semantic static relations between transactions are the inputs needed by the basic reconciler. In this section we describe how data relations are automatically inferred. the inference if log relations is discussed in the next section.

The common approach in semantics-based reconciliation is to require the definition of methods (e.g. IceCube [15]) or tables (e.g. Sync [10]) that specify semantics-based information/rules between two operations. This approach has two drawbacks. First, even when it is simple to specify each rule, it tends to be a repetitive, verbose and error-prone work. Second, it makes difficult to introduce new operations, as it is necessary to extend the rules for data relations. In a database system where generic mobile transactions may be submitted, this becomes an important issue.

In SqlIceCube we have designed a mechanism to automatically infer the data relations between mobile transactions. To this end, the code of mobile transactions is statically analyzed extracting a set of relevant information. This information is used to infer the relations between transactions. In this section we detail this mechanism.

Static analysis [5] of programs has been used before in several systems to verify the correctness [4, 1] and equivalence of programs [9]. However, to our knowledge, this work is the first to use a similar approach in reconciliation. Our static analysis presents the following uncommon characteristics: it is executed at reconciliation time and the information extracted from each program is used to infer relations between two programs (other than equivalence).

3.1. Extract information

To extract information from a mobile transaction, the transaction program is statically analyzed checking all execution paths. For each execution path that ends in a *commit* statement, the following group of information is extracted:

Semantic read set The *semantic read set* contains the semantic description of each relevant *read data item* (if the read value is not used, it is not relevant). This information is obtained from *select* statements.

```
1   BEGIN
2     SELECT stock,price INTO l_stock,l_price FROM products WHERE id = 80;
3         -- l_stock = read(products,id=80,stock)
4         -- l_price = read(products,id=80,price)
5     IF l_price <= 100 AND l_stock >= 10 THEN
6         -- as the contrary leads to a rollback
7         -- precond(read(products,id=80,stock)>=10 AND read(products,id=80,price)<=100)
8       UPDATE products SET stock = stock - 10 WHERE id = 80;
9         -- update(products,id=80,stock,stock-10)
10      INSERT INTO orders
11          VALUES (newid,8785,80,10,l_price,'to process');
12        -- insert(orders,(id,client,product,qty,price,status),(647,8785,80,10,l_price,'to process'))
13      COMMIT;
14    ELSE
15      ROLLBACK;
16    ENDIF;
17  END;
```

Figure 3: Information extracted from a mobile transaction that adds an order in a mobile sales application.

Semantic write set The *semantic write set* contains the semantic description of each *written data item*. This information is obtained from *insert*, *update* and *delete* statements.

Precondition set The *precondition set* contains all conditions in the given execution path. This information is obtained from *if* instructions.

The semantic description of a data item includes the name of the table, the name of the column and the condition used to refer the data item.

Figure 3 shows, as comments (lines starting with --), the information that can be extracted from the simple mobile transaction that adds a new order in a mobile sales application. The *select* statement at line 2 associates the semantic description of the read data item with the given variables.

During static analysis, both values should be considered for conditions specified in *if* instructions. In this example, as considering the condition false leads to a rollback, there is no need to consider this execution path. Considering the condition true leads to a commit statement. Therefore, the given condition is a precondition to the success of the transaction: the correspondent semantic precondition is added to the precondition set.

The semantic descriptions of written data items are directly extracted from the *update* and *insert* statements at lines 8 and 10-11. These descriptions compose the semantic write set for the transaction. The semantic read set is composed by all semantic descriptions of read data items that are used in the preconditions or write statements. In this case, as the data items read at line 2 are used in the precondition at line 5, the semantic read set is composed by the description of those read data items. From this mobile transaction, a single set of static information is extracted as there is only one execution path leading to a *commit* statement.

3.2. Infer relations

The relations between each pair of transactions are inferred by *comparing* the semantic information extracted from each transaction. As this information only contains the semantic description of each data item, it is necessary to verify if the conditions expressed in the different semantic

descriptions refer the same data items or not. This verification includes not only the data items read or written but also the data items used to select them (these data items are indirectly read). In database systems, similar analysis are executed in the context of query optimization [6] and semantic caching [3].

Given two transactions t_1 and t_2, each one with a single group of information, the following rules are used to infer each data relation.

Commute (default:false) t_1 does not commute with t_2 if t_1 reads a data item written by t_2 (or vice-versa), or t_1 writes a data item written by t_2 (or vice-versa) unless all t_1 writes commute with all t_2 writes (and vice-versa).

Helps (default:true) t_1 helps t_2 if t_1 writes changes the database in a favorable way for t_2 preconditions to be true. For example, increasing the value of a data item, x, helps the condition $x \geq const$ to be true.

Makes possible (default:false) t_1 makes possible t_2 if t_1 writes makes t_2 preconditions true. For example, setting the value of a data item x to a constant value c_1 makes the condition $x \geq c_2$ true if $c_1 \geq c2$.

Prejudices (default:true) t_1 prejudices t_2 if t_1 writes changes the database in a prejudicial way for t_2 preconditions to be true.

Makes impossible (default:false) t_1 makes impossible t_2 if t_1 writes makes t_2 preconditions false.

When there is more than one possible execution path in each program (and several groups of information are obtained from each transaction), it is necessary to analyze the different possible combinations. If different results are obtained, the default value is assumed.

Sometimes it is impossible to determine exactly if two semantic descriptions refer the same data item or not. For example, two *select* statements that read data item from the same table using conditions over different columns cannot be precisely compared. In this case, if the comparison's result is important to evaluate if some relation is established between two transactions, the default value for the relation is assumed.

The default values, presented in parenthesis before, were chosen to guarantee the safety of the reconciliation algorithm, as discussed elsewhere [14].

3.3. Examples

Now, we present two examples from typical mobile application that show how relations are inferred from the code of mobile transactions written in PL/SQL.

Mobile sales application:

In the first example, we consider two types of mobile transactions submitted in the context of a mobile sales application. The first, presented in figure 3, adds a new order. The second, cancels an order if it has not been processed yet, as shown in figure 4.

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```
BEGIN
  SELECT status INTO l_status FROM orders WHERE id = 3;        -- l_status = read(orders,id=3,status)
  IF l_status = 'to process' THEN                              -- precond(read(orders,id=3,status)='to process')
    UPDATE orders SET status = 'cancelled' WHERE id = 3;       -- update(orders,id=3,status,'cancelled')
    UPDATE products SET stock = stock + 30 WHERE id = 80;      -- update((products,id=80),stock,stock+30)
    COMMIT;
  ELSE
    ROLLBACK;
  ENDIF;
END;
```

Figure 4: Information extracted from a mobile transaction that cancels an order in a mobile sales application.

```
--- RESERVES ROOM 'Ballroom A' FOR DAY '16-FEB-2002' INFO 'Demo B THING'
BEGIN
  SELECT count(*) INTO cnt FROM datebook WHERE day='16-FEB-2002' AND room='Ballroom A';
        -- cnt = read(datebook,day='16-FEB-2002' AND room='Ballroom A',count(*))
  IF (cnt = 0) THEN
        -- precond(read(datebook,day='16-FEB-2002' AND room='Ballroom A',count(*))=0)
    INSERT INTO datebook VALUES( '16-FEB-2002', 'Ballroom A', 'Demo B THING');
        -- insert(datebook,(day,room,info),'16-FEB-2002','Ballroom A','Demo B THING'))
    COMMIT;
  ENDIF;
  ROLLBACK;
END;
```

Figure 5: Information extracted from a mobile transaction that inserts an appointment in a shared calendar.

The information that can be extracted from each mobile transaction is shown, as comments, in the figures[2]. Let *a* be an add order transaction and *c* be a cancel order transaction acting on the same product. The system infers the following relations. *a* and *c* do not commute, as *a* reads the stock of product with $id = 80$ and *c* writes (updates) it. *c* helps *a*, as adding a positive value to the stock helps the stock to be bigger than some constant. No other relations exist. The inferred relations are the expected ones, leading the reconciler to execute the cancel transaction before executing the add transaction, thus improving the chance of committing both transactions.

As expected, two mobile transactions adding a new order for the same product do not commute and each one prejudices the other, as subtracting a positive value from the stock reduces the chances of the stock being larger than some constant.

Two mobile transactions cancelling the same order do not commute and each one makes impossible the other, as setting the order state to *cancelled* makes the precondition expressed in the transaction false. This is the expected behavior as an order can only be cancelled once.

Two mobile transactions acting on different products and orders commute because they do not access the same data items.

---

[2] As explained before, this information is automatically extracted from the code of the mobile transaction: presenting it as comments in the code of transactions is just a convenience for showing the information that can be extracted from each statement.

```
-- REMOVE RESERVATION ROOM 'Ballroom A' FOR DAY '16-FEB-2002' INFO 'Demo B THING'
BEGIN
  SELECT count(*) INTO cnt FROM datebook WHERE day='16-FEB-2002' AND room='Ballroom A' AND info='Demo B THING';
     -- PATH1 and PATH 2:
     -- cnt = read(datebook,day='16-FEB-2002' AND room='Ballroom A' AND info='Demo B THING',count(*))
  IF (cnt > 0) THEN
     -- PATH 1 (then branch): precond(read(datebook,info='Demo B THING' AND
     --    day='16-FEB-2002' AND room='Ballroom A',count(*)) > 0)
     -- PATH 2 (else branch): precond(read(datebook,info='Demo B THING' AND
     --    day='16-FEB-2002' AND room='Ballroom A',count(*)) <= 0)
    DELETE FROM datebook WHERE day='16-FEB-2002' AND room='Ballroom A';
     -- PATH 1: delete(datebook,day='16-FEB-2002' AND room='Ballroom A')
  ENDIF;
  COMMIT;
END;
```

Figure 6: Information extracted from a mobile transaction that cancels an appointment in a shared calendar.

Shared calendar:

In the second example, we consider typical transactions submitted in the context of a shared calendar used to maintain meeting room reservations. The transaction presented in figure 5 adds a new reservation for a room, if possible. The transaction of figure 6 removes an existing reservation. If the reservation does not exist, the transaction still commits but nothing is done. In this case, two groups of semantic information are obtained, depending on the value assumed for the condition of the *if* statement.

The systems infers the following relations. Any two transactions that refer non-overlapping reservations commute as they access different data items. Transactions with overlapping reservations do not commute. For these transactions, the following additional relations are inferred.

For two transactions that insert a new reservation, each one makes impossible (and prejudices) the other, as the inserted record leads the precondition to be false.

For two transactions that cancel the same reservation, it is necessary to analyze the different combinations of possible paths. The delete statement of *path 1* makes the precondition of *path 1* false. Therefore, if *path 1* was the only possible execution path, each transaction would prejudice and make the other transaction impossible. However, the delete statement of *path 1* helps and makes possible the precondition of *path 2*. Therefore, the default values should be assumed: each transaction helps and prejudices the other, leading to a null net effect in the heuristic defined in section 2.3, as expected.

For a transaction, a, that inserts a new reservation and a transaction, c, that cancels a reservation, two cases should be considered. If transactions refer to different reservations (i.e. the value of the info field is different), c helps a as removing the reservation guarantees that it is possible to schedule a new reservation for that time and place (c does not makes possible a as *path 2* of c does not make possible a). Thus, as expected, the reconciler will cancel appointments before trying to schedule new appointments for the same time and place.

If a and c refer the same reservation (i.e. the value of the info field is equal), either c is cancelling the reservation previously inserted by a, or c is cancelling a reservation that already exists in the database. In the first case, both transactions should have been submitted in the same mobile client and the suitable strong predecessor-successor log constraint is inferred, as

explained in the next section. Thus, *a* is executed before *c*, as expected. In the second case, *a* helps and prejudices *c* because the inserted record guarantees that the reservation exists, leading the precondition of *path 1* and *path 2* of *c* to be, respectively, true and false. Default values are assumed for makes possible and makes impossible, as different values are obtained in different combination. Therefore, *a* has no net influence over *c*. *c* helps *a* because removing the reservation guarantees that it is possible to schedule a new reservation for that time and place. Thus, the SqlIceCube reconciler executed *c* before executing *a*, as expected.

4. Extensions and on-going work

In this section we discuss some extensions to the basic solution described so far.

4.1. Comparison of semantic descriptions

Sometimes it is impossible to compare precisely two semantic descriptions because they include conditions over different columns of the same table or indirections (i.e., they use values read in previous *select* statements). This problem can be solved reading from the database the extra information needed to solve indirections or to *compare* conditions precisely. As, in many cases, the data items used cannot be modified by any transaction under reconciliation, it is possible to read the current values from the database and use them, as constants, to infer static relations.

4.2. Loops

The modification of multiple records using a single SQL statement is addressed by the basic approach described so far. However, to process transactions that include loops (controlled by a cursor or not), we need to consider the following two cases. First, when the sequence of values for the variable that controls the loop is (directly or indirectly) known (e.g. in *"for i in 1..3 loop"*, *i* will be assigned the values 1,2 and 3), the analysis is trivial — it is just necessary to evaluate the code inside the loop once for each value of the control variable. Second, when the sequence of values for the control variable is not known, it may be very difficult or impossible to extract precise information. We are currently investigating this problem.

4.3. Complex transactions and log constraints

Our semantic inference module may have problems to handle very long transactions that access many data items, as these transactions may end up having all types of relations with (many of) the other transactions. To avoid this problem, the SqlIceCube API allows programmers to submit complex operations as a composition of smaller transactions linked by suitable log relations. These log relations cannot be automatically inferred as they encode users intents and they are not expressed in the code of transactions.

However, some log relations can be automatically inferred. To this end, the SqlIceCube system may pre-process each transaction received, splitting it into smaller transactions linked by suitable log relations. For example, a transaction composed by a set of alternative transactions coded as a sequence of *if* instructions can be split into an ordered set of alternative transactions (using the *alternatives* and *weak predecessor-successor* log relations), each one with a single alternative transaction. Other log relations can also be automatically inferred between transactions submitted in the same mobile client — e.g. if a transaction reads a data item inserted by a previous transaction, the *strong predecessor-successor* log relation can be added between the older and the new transaction.

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5. Final Remarks

SqlIceCube is a general-purpose semantics-based reconciliation system for mobile databases. The system includes a semantic inference module that automatically extracts semantic information from the code of mobile transactions. This information, exposed as a set of static relations among transactions, is used by the basic reconciler to create near-optimal reconciliation results. To our knowledge, SqlIceCube is the first to automatically infer the semantic information needed in reconciliation. This approach simplifies the use of semantics-based reconciliation by eliminating the overhead of writing long/complex rules to expose the semantics of operations. SqlIceCube basic reconciler is based on the IceCube reconciler [15], the first to treat reconciliation as an optimization problem. Some changes have been made to accommodate mobile transactions.

SqlIceCube has been initially developed to be used in Mobisnap, as a complement of the reservation (conflict-avoidance) mechanism [13]. However, SqlIceCube is an architecture-independent reconciliation system that can be easily used in other SQL-based systems — e.g. in Bayou [18], it could be used in the primary server to order updates received in epidemic communication sessions (if updates were expressed in PL/SQL).

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