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Performance Issues in Incremental Warehouse Maintenance[*]

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Abstract

A well-known challenge in data warehousing is the efficient incremental maintenance of warehouse data in the presence of source data updates. In this paper, we identify several critical data representation and algorithmic choices that must be made when developing the machinery of an incrementally maintained data warehouse. For each decision area, we identify various alternatives and evaluate them through extensive experiments. We show that picking the right alternative can lead to dramatic performance gains, and we propose guidelines for making the right decisions under different scenarios. All of the issues addressed in this paper arose in our development of WHIPS, a prototype data warehousing system supporting incremental maintenance.

1 Introduction

Data warehousing systems integrate and store data derived from remote information sources as *materialized views* in the warehouse [LW95, CD97]. When source data changes, warehouse views need to be modified (*maintained*) so that they remain consistent with the source data. A well-known challenge in data warehousing is reducing the time required for warehouse maintenance [LYGM99]. Commercial data warehousing systems typically recompute all warehouse views periodically in order to keep them up to date. For views defined over large volumes of remote source data, full recomputation can be very expensive. In contrast, the *incremental* approach to warehouse maintenance only computes and installs the incremental changes to the views based on the source updates [GM95]. Because of its potential performance advantage over full recomputation, incremental view maintenance has found its way recently into commercial systems, e.g., [FS96, BDD$^+$98, BS99]. Although the subject also has enjoyed considerable attention from the research community [GM95], very little research to date covers the detailed but important data representation and algorithmic choices that must be made when developing the machinery of an incrementally maintained data warehouse.

These choices arose in our development of WHIPS (W*are*H*ouse* I*nformation* P*rocessing* S*ystem*), a prototype data warehousing system at Stanford [WGL$^+$96]. WHIPS manages the loading and incremental maintenance of warehouse data, which is integrated from multiple remote sources and stored in a commercial database management system. In the following basic example, we illustrate some of the choices we were confronted with concerning the representation of warehouse views.

Example 1.1 Consider a source table $R(K, A_1, A_2, ..., A_n)$ with key attribute K, and a simple warehouse view $V(A_1, A_2, ..., A_n)$ defined over R which projects out the key of R. The first decision to make is whether we should preserve duplicates in V (*bag semantics*) or eliminate them (*set semantics*). Our experience with WHIPS tells us that bag semantics is preferred for warehouse data for two reasons. First, duplicates may be required by data analysis or OLAP applications, e.g., those that perform additional aggregation

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over V. Second, duplicates simplify incremental maintenance. Suppose we choose instead to eliminate duplicates from V. When a tuple $\langle k, a_1, a_2, ..., a_n \rangle$ is deleted from R, we cannot decide whether to delete $\langle a_1, a_2, ..., a_n \rangle$ from V without querying R, because there might exist another tuple $\langle k', a_1, a_2, ..., a_n \rangle$ in R, which also derives $\langle a_1, a_2, ..., a_n \rangle$ in V. On the other hand, if duplicates are preserved in V, we know that we should always delete one tuple from V for each tuple deleted from R; no queries over R are needed for incremental maintenance. (Bag semantics are also useful for many more complex cases of incremental maintenance, beyond the simple view of this example.)

Now suppose that based on the deletions from R we have computed $\bigtriangledown V$, a bag of tuples to be deleted from V. To apply $\bigtriangledown V$ to V, one might be tempted to use the following SQL statement:

DELETE FROM V WHERE (A_1, A_2, ..., A_n) IN (SELECT * FROM $\bigtriangledown V_1$)

Unfortunately, this statement does not work because SQL `DELETE` always removes *all* tuples satisfying the `WHERE` condition. If V has three copies of a tuple t and $\bigtriangledown V$ contains two copies of t, the above `DELETE` statement will delete all three copies from V, instead of correctly leaving one. To properly apply $\bigtriangledown V$, we need to use a cursor on $\bigtriangledown V$ (details will be provided later). However, a cursor-based implementation forces $\bigtriangledown V$ to be processed one tuple at a time. This restriction, among other performance considerations, leads us to investigate a different representation for warehouse view V in which we store only one copy for each tuple, together with an extra *dupcnt* attribute to record the number of duplicates for that tuple. Under this "count" representation, $\bigtriangledown V$ can be applied in batch with two SQL statements (again, details will be given later). Besides the obvious advantage of being more compact when the number of duplicates is large, how does this count representation compare with the default duplicate representation? In particular, does it speed up overall view maintenance? Are SQL statements really better than a cursor loop for applying $\bigtriangledown V$? These are examples of the questions that we have asked ourselves when building WHIPS, and they are answered in this paper through extensive experiments. $\square$

In addition to the questions raised above, there are several other decision areas that we have encountered, such as strategies for aggregate view maintenance and index maintenance. In this paper, we identify a set of specific but important areas in which a data warehousing system must make critical decisions on view representation and maintenance. For each decision area, we propose various alternatives, including interesting new variations for aggregate view maintenance that turn out to have important advantages over previous algorithms in some cases. In many of the decision areas we discuss, making a wrong decision can severely hamper the efficiency of warehouse maintenance. For example, as we will see in our experiments, change installation times can vary by orders of magnitude depending on how maintenance is implemented: as data volumes grow, picking the right strategy can mean the difference between a few minutes and many hours of warehouse maintenance time. Based on the results of our experiments, we provide guidelines for making right decisions under different scenarios. We have used WHIPS as the testbed for our study since WHIPS is representative of data warehousing infrastructures built on top of commercial database systems. We believe that our results have applicability well beyond WHIPS—they should prove helpful to any implementation of incremental warehouse maintenance either within or on top of a commercial DBMS.

The rest of the paper is organized as follows. In Section 2, we give an overview of the WHIPS architecture, which sets the stage for later discussions. In Section 3, we focus on the component of WHIPS responsible for warehouse maintenance and discuss the various choices in building its view maintenance machinery. In Section 4, we conduct experiments to evaluate each alternative and present guidelines for making the best choices. Finally, we discuss related work in Section 5 and conclude the paper in Section 6.

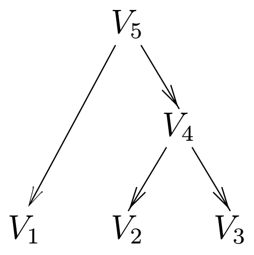

Figure 1: Conceptual organization.

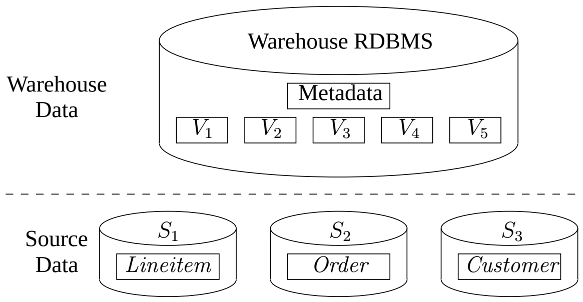

Figure 2: Physical organization.

2 WHIPS Architecture

2.1 Data Organization in WHIPS

The warehouse views incrementally maintained by WHIPS are derived from one or more independent data sources. Currently, source data incorporated by WHIPS may be brought in from flat files or relational tables, and it may reside in remote information sources.

Data in the warehouse is modeled conceptually using a *view directed acyclic graph* (*VDAG*). Each node in the graph represents a materialized view stored at the warehouse. An edge $V_j \rightarrow V_i$ indicates that view V_j is defined over view V_i. A node with no outgoing edges represents a view that is defined over source data. WHIPS requires that each warehouse view V is defined either only over source data, or only over other warehouse views, because views defined over source data require special algorithms for ensuring their consistency [ZGMHW95]. We call views defined over source data *base views*, and views defined over other warehouse views *derived views*. (In a typical OLAP-oriented data warehouse, fact tables and dimension tables would be modeled as base views, while summary tables would be modeled as derived views.) Figure 1 shows a simple example of a VDAG with three base views V_1, V_2, and V_3, and two derived views V_4 and V_5. The source data from which the base views V_1, V_2, and V_3 are derived is not represented in the VDAG.

The top half of Figure 2 shows that WHIPS physically stores views V_1–V_5 from Figure 1 as tables in a relational DBMS, along with metadata that records each view's definition. The metadata also stores information about the source data from which the base views are derived. In WHIPS, each base view is defined over source data using a single SQL `SELECT-FROM-WHERE` (SFW) statement. This simple base view definition language allows the warehouse designer to filter and combine source data using appropriate selection and join conditions in the `WHERE` clause. Currently, aggregation is not permitted in base view definitions because it is difficult to ensure the consistency of aggregates over remote source relations [ZGMHW95].

Each derived view is defined over other warehouse views using one or more SQL `SELECT-FROM-WHERE-GROUP-BY` (SFWG) statements, where aggregation is permitted. Multiple SFWG statements may be combined using the SQL `UNION ALL` operator.

Example 2.1 As a concrete example, let us suppose that there are three remote information sources S_1, S_2, and S_3 as shown in the bottom half of Figure 2, exporting the TPC-D tables [TPC96] $Lineitem$, $Order$, and $Customer$ respectively. Base views V_1, V_2, and V_3 at the warehouse could be defined as projections over $S_1.Lineitem$, $S_2.Order$ and $S_3.Customer$ as follows (attributes have been renamed for simplicity):

```
CREATE VIEW V1 AS
  SELECT orderID, partID, qty, cost FROM S1.Lineitem
```

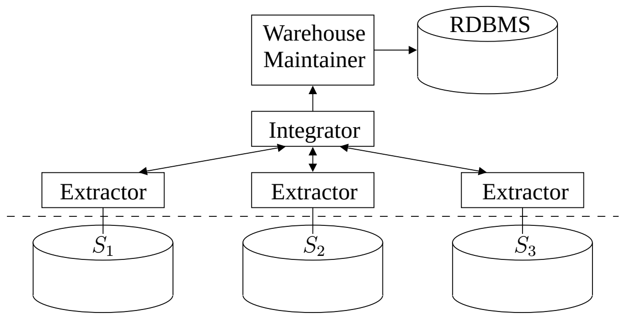

Figure 3: WHIPS components.

```
CREATE VIEW $V_2$ AS
  SELECT $orderID$, $custID$, $date$ FROM $S_2.Order$

CREATE VIEW $V_3$ AS
  SELECT $custID$, $name$, $address$ FROM $S_3.Customer$
```

Of course, selection and join operations may be used in base view definitions as well. Derived view V_4 could be defined to count the number of orders each customer has made in 1998:

```
CREATE VIEW $V_4$ AS
SELECT $custID$, COUNT(*)
FROM $V_2$, $V_3$
WHERE $V_2.custID$ = $V_3.custID$ AND $V_2.date$ >= '1998-01-01' AND $V_2.date$ < '1999-01-01'
GROUP BY $custID$
```
□

2.2 Overview of WHIPS Components

Three types of components comprise the WHIPS system: the *Extractors*, the *Integrator*, and the *Warehouse Maintainer*. As mentioned previously, WHIPS also relies on a commercial relational DBMS as its backend to store and process warehouse data. This approach to building a data warehousing system exploits the well-developed capabilities of the DBMS for handling large volumes of data, and thereby avoids "reinventing the wheel." The WHIPS components, along with the DBMS, are shown in Figure 3. We now discuss the WHIPS components by walking through how warehouse data is maintained when source data changes.

Each Extractor component periodically detects *deltas* (insertions, deletions, and/or updates) in source data. One Extractor is used for each information source. Each table (for a relational source) or file (for a flat file source) that is referred to in the `FROM` clause of any base view definition is monitored. For instance, in Figure 3, the Extractor assigned to S_1 detects the changes to the $Lineitem$ table which resides in S_1.

The Integrator component receives deltas detected by the Extractors, and computes a consistent set of deltas to the base views stored in the warehouse. The Integrator may need to send queries back to the sources to compute base view deltas. For details, see [WGL$^+$96, ZGMHW95].

The Warehouse Maintainer component receives the base view deltas from the Integrator and computes a consistent set of deltas to the derived views. The Warehouse Maintainer then updates all of the warehouse views based on the provided and computed deltas. To compute the derived view deltas and update the

orderID	*partID*	*qty*	*cost*
1	*a*	1	20
1	*b*	2	250
1	*a*	1	20

Figure 4: DUP representation (V_1^{DUP}).

orderID	*partID*	*qty*	*cost*	*dupcnt*
1	*a*	1	20	2
1	*b*	2	250	1

Figure 5: CNT representation (V_1^{CNT}).

materialized views, the Warehouse Maintainer sends a sequence of Data Manipulation Language (DML) commands to the DBMS. These DML commands include SQL queries for computing the deltas, as well as modification statements (e.g., `INSERT`, `DELETE`, cursor updates) for updating the materialized views.

The interaction among the WHIPS components when warehouse data is first loaded is similar to the description above for maintenance. First, the Extractors identify the source data needed to load the warehouse based on the base view definitions. The Integrator then computes a consistent set of initial base views using the source data from the Extractors. The Warehouse Maintainer in turn computes a consistent set of initial derived views, and then sends a sequence of Data Definition Language (DDL) and DML commands to the DBMS. The DDL commands (e.g., `CREATE TABLE`) are used for creating the materialized views. The DML commands are used for initially populating the materialized views.

In the remainder of the paper, we shall focus on the Warehouse Maintainer component. We refer the reader to [LGM96] and [ZGMHW95] for extended discussions of the Extractor and Integrator components, respectively.

3 The Warehouse Maintainer

The Warehouse Maintainer is the component responsible for initializing and maintaining the warehouse views. There are many possible ways of representing the warehouse views and performing incremental maintenance on them. In Sections 3.1–3.3, we identify specific important decision areas. For each decision area, we propose several alternatives and analyze them qualitatively. Quantitative performance results will be presented in Section 4. We have decided to separate the performance results from the discussion of the decision areas (rather than mixing them), because some of the decision areas are interrelated and it is important to have a complete overview of the issues before we delve into the detailed performance analysis.

3.1 View Representation and Delta Installation

Views in WHIPS are defined using SQL SFWG statements (for derived views) and SFW statements (for base views) with bag semantics. There are two ways to represent a bag of tuples in a view. One representation, which we call the DUP representation, simply keeps the duplicate tuples, as shown in Figure 4 for a small sample of data in view V_1 from Example 2.1. Another representation, which we call the CNT representation, keeps one copy of each unique tuple and stores the number of duplicates in a special *dupcnt* attribute, as in Figure 5. Let us denote a view V's DUP representation as V^{DUP} and its CNT representation as V^{CNT}. Next, we compare the two representations in terms of their storage costs and implications for queries and view maintenance.

3.1.1 Storage Cost and Query Performance

The CNT representation of a view V has lower storage cost if there are many duplicates in V and if the tuples of V are large enough that the storage overhead of having a *dupcnt* attribute is not significant. The reduction in storage achieved by using V^{CNT} instead of V^{DUP} may speed up selection, join, and aggregation queries over V by reducing I/O. However, projections may be slower when the CNT representation is used. Consider the simple operation of listing the *orderID*'s in V_1:

```
SELECT orderID FROM V1
```

If we operate directly on the CNT representation V_1^{CNT} (Figure 5), the answer to the above query will not remain in the CNT representation, and the duplicates in the result will not be meaningful. For the answer to be in the CNT representation, we need to group the tuples with matching *orderID*'s and sum up their *dupcnt* values:

```
SELECT orderID, SUM(dupcnt) AS dupcnt FROM V1^CNT GROUP BY orderID
```

In general, whenever projection is used in a query, aggregation may be necessary to produce an answer in the CNT representation.

3.1.2 Deletion Installation

If V has no duplicates, then the deletions from V, denoted $\bigtriangledown V$, can be installed using a single DELETE statement, regardless of whether V is represented using DUP or CNT. For example, to install $\bigtriangledown V_1$ in our working example, we use:

```
DELETE FROM V1
WHERE (V1.orderID, V1.partID) IN (SELECT orderID, partID FROM ▽V1)
```

The above statement works for both DUP and CNT representations, assuming that $\{orderID, partID\}$ is a key for V_1. The WHERE clause can be modified appropriately to handle keys with arbitrary number of attributes. In the worst case, all attributes of the view together form a key, provided that the view contains no duplicates. Unfortunately, when V_1 has duplicates and hence no key, the above DELETE statement is incorrect because it may delete more tuples than intended, as discussed in Example 1.1.

In general, care must be taken when installing $\bigtriangledown V$. Under the DUP representation, a cursor on $\bigtriangledown V^{\text{DUP}}$ is required. For each tuple t in $\bigtriangledown V^{\text{DUP}}$ examined by the cursor, we delete one and only one tuple in V^{DUP} that matches t. Doing so generally requires another cursor on V^{DUP}. However, if the DBMS provides some mechanism of restricting the number of rows processed by a statement (such as allowing statements to reference row counts or tuple ID's), then we can avoid the additional cursor on V^{DUP}.

Under the CNT representation, each deleted tuple t in $\bigtriangledown V^{\text{CNT}}$ results in either an update to or a deletion from V^{CNT}. If $t.dupcnt$ is less than the *dupcnt* value of the tuple in V^{CNT} that matches t, we decrement the matching V^{CNT} tuple's *dupcnt* value by $t.dupcnt$. Otherwise, we delete the matching tuple from V^{CNT}. This procedure can be implemented with a cursor on $\bigtriangledown V^{\text{CNT}}$. Alternatively, the entire $\bigtriangledown V^{\text{CNT}}$ can be processed in batch with one UPDATE statement and one DELETE statement, but both statements contain potentially expensive correlated subqueries. The DELETE statement is illustrated below. The UPDATE statement is twice as long, with one correlated subquery in its WHERE clause and one in its SET clause. We omit the details due to space constraints.

```
DELETE FROM $V^{\text{CNT}}$
WHERE EXISTS (SELECT * FROM $\bigtriangledown V^{\text{CNT}}$
              WHERE $\bigtriangledown V^{\text{CNT}}.orderID$ = $V^{\text{CNT}}.orderID$
              AND   $\bigtriangledown V^{\text{CNT}}.partID$ = $V^{\text{CNT}}.partID$
              AND   $\bigtriangledown V^{\text{CNT}}.dupcnt$ >= $V^{\text{CNT}}.dupcnt$)
```

3.1.3 Insertion Installation

Under the DUP representation, we can install the insertions into V^{DUP}, denoted $\triangle V^{\text{DUP}}$, using a single straightforward SQL `INSERT` statement. Under the CNT representation, we can install $\triangle V^{\text{CNT}}$ with a single `INSERT` statement only if we know that V never contains any duplicates. In general, however, each tuple t in $\triangle V^{\text{CNT}}$ results in either an update or an insertion to V^{CNT}. If there is a tuple in V^{CNT} that matches t, we increment the matching V^{CNT} tuple's $dupcnt$ value by $t.dupcnt$. Otherwise, we insert t into V^{CNT}. Again, this procedure can be implemented with a cursor on $\triangle V^{\text{CNT}}$, or we can process the entire $\triangle V^{\text{CNT}}$ in batch with one `UPDATE` statement and one `INSERT` statement, but again, both statements contain potentially expensive correlated subqueries.

3.1.4 Discussion

Intuitively, for a warehouse view that never contains any duplicates (i.e., it has a known key), the DUP representation should outperform the CNT representation in all metrics (storage cost, query performance, and delta installation time) because the DUP representation does not have the overhead of one $dupcnt$ attribute per tuple. On the other hand, for a view with many duplicates, we would expect the CNT representation to be preferable because it is more compact. For WHIPS, we are interested in knowing, quantitatively, which representation is better as we vary the average number of duplicates in a view. In addition, we would like to quantify the overhead of the CNT representation for views with no duplicates.

Another issue we wish to investigate is the strategy for delta installation. As discussed earlier in this section, delta installation becomes much simpler if we know that the view will not contain duplicates. Let KEYINSTALL denote the method of installing deltas that exploits a lack of duplicates (i.e., a known key), and let GENINSTALL denote the general method that does not. It is easier for the Warehouse Maintainer component to support only GENINSTALL because it works for all views with or without keys. However, warehouse views frequently do have keys. For instance, dimension tables and fact tables, which are modeled as base views, usually have keys. Summary tables (or derived views) often perform `GROUP-BY` operations, and the `GROUP-BY` attributes become the keys of the summary tables. If KEYINSTALL consistently outperforms GENINSTALL for these common cases, the Warehouse Maintainer should support KEYINSTALL as well.

Finally, we also need to evaluate different implementations of GENINSTALL under the CNT representation. As discussed earlier, GENINSTALL under the CNT representation can be implemented either with a cursor loop or with two SQL statements with subqueries. (Under the DUP representation, GENINSTALL must be implemented with a cursor loop.) With a cursor loop, we have better control over the execution of the installation procedure, so we can optimize it by hand according to our knowledge of the warehouse workload. On the other hand, the SQL statements are optimized by the DBMS, armed with a more sophisticated performance model and statistics. Although traditional DBMS optimizers were not designed originally for data warehousing, modern optimizers have added considerable support for warehouse-type

orderID	*partID*	*qty*	*cost*
1	*a*	1	20
1	*b*	2	250
2	*a*	1	20
3	*c*	1	500

Figure 6: V_1.

partID	*revenue*	*tuplecnt*
a	40	2
b	500	1
c	500	1

Figure 7: $Parts$.

data and queries [CD97]. It is interesting to determine whether the SQL-based delta installation procedure can be optimized adequately by the DBMS we are using.

In Section 4.1, we present answers to all of the questions discussed above based on the experiments we have conducted in WHIPS.

3.2 Maintaining Aggregate Views

Given deltas for base views, the Warehouse Maintainer needs to modify the derived views so that they remain consistent with the base views. A simple approach is to recompute all of the derived views from the new contents of the base views, as many existing warehousing systems do. WHIPS, on the other hand, maintains the derived views incrementally for efficiency. The Warehouse Maintainer first computes the deltas for the derived views using a predefined set of queries called *maintenance expressions*, and then it installs these deltas into the derived views. The maintenance expressions of views defined using SQL SFW statements (without subqueries) are well studied, e.g., [GL95], and we do not discuss them here. For views defined using SQL SFWG statements (i.e., views with `GROUP-BY` and aggregation), we will introduce and contrast four different maintenance algorithms through a comprehensive example.

In this example, let us suppose that view V_1 contains the tuples shown in Figure 6. A view $Parts$ is defined over V_1 to group the V_1 tuples by $partID$. The $revenue$ of each part stored in $Parts$ is computed from V_1 by summing the products of qty and $cost$ for each order for that particular part. $Parts$ also records in a $tuplecnt$ attribute the number of V_1 tuples that are used to derive each $Parts$ tuple. The SQL definition of $Parts$ is as follows:

```
CREATE VIEW Parts AS
SELECT partID, SUM(qty*price) AS revenue, COUNT(*) AS tuplecnt
FROM V1 GROUP BY partID
```

The tuples in $Parts$ are shown in Figure 7. We use the DUP representation for $Parts$ since $Parts$ has a key ($partID$) and hence contains no duplicates. Note that the $tuplecnt$ attribute differs from the $dupcnt$ attribute used under the CNT representation since $tuplecnt$ does not reflect the number of duplicates in $Parts$. Nevertheless, like $dupcnt$, $tuplecnt$ helps incremental view maintenance by recording the number of base view tuples that contribute to each derived view tuple: The $tuplecnt$ attribute is used to determine when a $Parts$ tuple t should be deleted because all of the V_1 tuples that derive t have been deleted from V_1. In fact, had $tuplecnt$ not been included in $Parts$'s definition, WHIPS would automatically modify the view definition to include $tuplecnt$ so that $Parts$ could be maintained incrementally.

Now suppose that the tuples shown in Figure 8 are to be inserted into V_1, and the ones shown in Figure 9 are to be deleted. (Note that tuples $\langle 1, a, 1, 20\rangle$ in $\bigtriangledown V_1$ and $\langle 1, a, 2, 20\rangle$ in $\bigtriangleup V_1$ together represent an update

orderID	*partID*	*qty*	*cost*
1	*a*	2	20
4	*c*	1	500
4	*d*	1	30

Figure 8: $\triangle V_1$.

orderID	*partID*	*qty*	*cost*
1	*a*	1	20
1	*b*	2	250

Figure 9: $\bigtriangledown V_1$.

in which the qty of a parts purchased in the first order ($orderID = 1$) is increased from 1 to 2.) Next we illustrate how we can maintain $Parts$ given the deltas $\bigtriangledown V_1$ and $\triangle V_1$, using four different algorithms.

3.2.1 Full Recomputation

Full recomputation (FULLRECOMP) is conceptually simple and easy to implement. First, we install the base view deltas $\bigtriangledown V_1$ and $\triangle V_1$ into V_1. Then, we delete the entire old contents of $Parts$ and compute its new contents from V_1.

3.2.2 Summary-Delta With Cursor-Based Installation

The original *summary-delta* algorithm for incremental maintenance of aggregate views [MQM97] (SDCURSOR for short) has a *compute phase* and a cursor-based *install phase*. In the compute phase, the net effect of $\triangle V_1$ and $\bigtriangledown V_1$ on $Parts$ is captured in a *summary-delta* table, denoted $Parts_{\mathrm{SD}}$ and computed as follows:

```
SELECT partID, SUM(revenue) AS revenue, SUM(tuplecnt) AS tuplecnt
FROM ((SELECT partID, SUM(qty*price) AS revenue, COUNT(*) AS tuplecnt
       FROM △V1 GROUP BY partID)
      UNION ALL
      (SELECT partID, -SUM(qty*price) AS revenue, -COUNT(*) AS tuplecnt
       FROM ▽V1 GROUP BY partID))
GROUP BY partID
```

The summary-delta applies the GROUP-BY and aggregation operations specified in the definition of $Parts$ to $\triangle V_1$ and $\bigtriangledown V_1$ and combines the results. Note that the aggregate values computed from $\bigtriangledown V_1$ are negated to reflect the effects of deletions on the SUM and COUNT functions. Given the $\triangle V_1$ and $\bigtriangledown V_1$ shown in Figures 8 and 9, the summary-delta $Parts_{\mathrm{SD}}$ is shown in Figure 10.

In the install phase, SDCURSOR instantiates a cursor to loop over the tuples in the summary-delta $Parts_{\mathrm{SD}}$. For each $Parts_{\mathrm{SD}}$ tuple, SDCURSOR applies the appropriate change to $Parts$. For instance, tuple $\langle a, 20, 0\rangle$ affects $Parts$ by incrementing the a tuple's $revenue$ by 20 and $tuplecnt$ by 0. This change reflects the effect of updating the qty of a parts in the first order (see $\bigtriangledown V_1$ and $\triangle V_1$). The $tuplecnt$ is unchanged because the update does not change the number of V_1 tuples that derive the a tuple in $Parts$. Tuple $\langle b, -500, -1\rangle$ in $Parts_{\mathrm{SD}}$ affects $Parts$ by decrementing the b tuple's $revenue$ by 500 and $tuplecnt$ by 1, which reflects the effect of deleting $\langle 1, b, 2, 250\rangle$ from V_1 (see $\bigtriangledown V_1$). Moreover, the b tuple is then deleted from $Parts$, since its $tuplecnt$ becomes zero after it is decremented. Tuple $\langle c, 500, 1\rangle$ increments the c tuple's $revenue$ by 500 and $tuplecnt$ by 1, reflecting the effect of inserting $\langle 4, c, 1, 500\rangle$ into V_1 (see $\triangle V_1$). Finally, tuple $\langle d, 30, 1\rangle$ results in an insertion into $Parts$, since there is no previous $Parts$ tuple with a $partID$ of d.

partID	*revenue*	*tuplecnt*
a	20	0
b	−500	−1
c	500	1
d	30	1

Figure 10: $Parts_{\mathrm{SD}}$.

partID	*revenue*	*tuplecnt*
a	20	1
b	500	1
c	500	1

Figure 11: $\bigtriangledown Parts$.

partID	*revenue*	*tuplecnt*
a	40	1
c	1000	2
d	30	1

Figure 12: $\bigtriangleup Parts$.

3.2.3 Summary-Delta With Batch Installation

The summary-delta algorithm with batch installation (SDBATCH) is a variation we propose in this paper on the original summary-delta algorithm from [MQM97] described above. The idea is to do more processing in the compute phase in order to speed up the install phase, since views must be locked during installation. In the compute phase of SDBATCH, we first compute the summary-delta $Parts_{\mathrm{SD}}$ as before. From $Parts_{\mathrm{SD}}$, we then compute the deletions $\bigtriangledown Parts$ and insertions $\bigtriangleup Parts$ to be applied to $Parts$. $\bigtriangledown Parts$ contains all the $Parts$ tuples that are affected by $Parts_{\mathrm{SD}}$, computed as follows:

```
SELECT * FROM Parts
WHERE partID IN (SELECT partID FROM Parts_SD)
```

$\bigtriangleup Parts$ is the result of applying $Parts_{\mathrm{SD}}$ to $\bigtriangledown Parts$, computed as follows:

```
SELECT partID, SUM(revenue) AS revenue, SUM(tuplecnt) AS tuplecnt
FROM ((SELECT * FROM ▽Parts) UNION ALL (SELECT * FROM Parts_SD))
GROUP BY partID
HAVING SUM(tuplecnt) > 0
```

Notice that we filter out those groups with *tuplecnt* less than one because they no longer contain any tuples after $Parts_{\mathrm{SD}}$ is applied. Given the $Parts_{\mathrm{SD}}$ shown in Figure 10, the resulting $\bigtriangledown Parts$ and $\bigtriangleup Parts$ are shown in Figures 11 and 12.

In the install phase of SDBATCH, we first apply $\bigtriangledown Parts$, and then $\bigtriangleup Parts$, to $Parts$. Because of the way we compute $\bigtriangledown Parts$ in the compute phase, every $\bigtriangledown Parts$ tuple always results in a true deletion from $Parts$, instead of an update that decrements the *revenue* and *tuplecnt* attributes of an existing $Parts$ tuple. Since $Parts$ is an aggregate view and hence contains no duplicates, the entire $\bigtriangledown Parts$ can be applied in batch using KEYINSTALL with a simple `DELETE` statement (Section 3.1.2). Once $\bigtriangledown Parts$ has been applied to $Parts$, every $\bigtriangleup Parts$ tuple always results in a true insertion into $Parts$, instead of an update that increments the *revenue* and *tuplecnt* attributes of an existing tuple. Therefore, $\bigtriangleup Parts$ can be applied in batch using KEYINSTALL with a simple `INSERT` statement.

3.2.4 Summary-Delta With Overwrite Installation

Both SDCURSOR and SDBATCH update $Parts$ in place, which requires identifying the $Parts$ tuples affected by the $Parts_{\mathrm{SD}}$ tuples. To avoid this potentially expensive operation, we introduce a new summary-delta algorithm with overwrite installation (SDOVERWRITE). SDOVERWRITE completely replaces the old contents of $Parts$ with the new contents, just like FULLRECOMP. However, SDOVERWRITE differs from FULLRECOMP in that SDOVERWRITE does not recompute $Parts$ from scratch; instead, it uses the summary-delta $Parts_{\mathrm{SD}}$ and the old contents of $Parts$ to compute the new $Parts$. The SQL statement used here is similar to the one used to compute $\triangle Parts$ in SDBATCH:

```
SELECT partID, SUM(revenue) AS revenue, SUM(tuplecnt) AS tuplecnt
FROM ((SELECT * FROM Parts) UNION ALL (SELECT * FROM Parts_SD))
GROUP BY partID
HAVING SUM(tuplecnt) > 0
```

One technicality remains: there is no easy way to replace the contents of $Parts$ with the results of the above SELECT statement since the statement itself references $Parts$. To avoid unnecessary copying, we store the results of the above query in another table, and then designate that table as the new $Parts$. Therefore, compared to the other three algorithms, SDOVERWRITE requires additional space roughly the size of $Parts$.

3.2.5 Discussion

Although the example in this section only shows how the various algorithms can be used to maintain a specific aggregate view, it is not hard to extend the ideas to handle views with arbitrary combinations of SUM, COUNT, and AVG aggregate functions. For views with MAX or MIN, SDCURSOR, SDBATCH, and SDOVERWRITE are not applicable in general, since we cannot perform true incremental maintenance when a base tuple providing the MAX or MIN value for its group is deleted; in that case, the base data must be queried.

To summarize, we have presented four algorithms for maintaining SFWG views. FULLRECOMP recomputes the entire view from scratch. Intuitively, if the base data is large, FULLRECOMP can be very expensive. SDCURSOR, SDBATCH, and SDOVERWRITE avoid recomputation by applying only the incremental changes captured in a summary-delta table. These three algorithms differ in the ways they apply the summary-delta to the view.

In WHIPS, we are interested in knowing which one of the four algorithms is best in different settings. We also wish to compare how long the different algorithms must lock the view for update. This measure is important because once a view is locked for update, it generally becomes inaccessible for OLAP queries. FULLRECOMP needs to lock while it is regenerating the view. SDCURSOR and SDBATCH only need to lock the view during their install phases. SDOVERWRITE does not lock the view at all, because it computes the new contents of the view in a separate table. In fact, with an additional table, we can also eliminate the locking time of FULLRECOMP, SDCURSOR, SDBATCH, or any maintenance algorithm in general, since we can always work on a copy of the view while leaving the original accessible to queries. In this case, it is useful to know how much locking time we are saving in order to justify the additional storage cost. In Section 4.2, we experimentally compare the performance and locking time of the four algorithms.

So far, we have focused on how WHIPS maintains a single view. In practice, WHIPS maintains a set of views organized in a VDAG (Section 2). When a view V is modified, other views defined over V need to be modified as well. In order to maintain the other views incrementally, we must be able to capture the incremental changes made to V. Among our four algorithms for aggregate view maintenance, only SDBATCH explicitly computes the incremental changes to V as delta tables $\bigtriangledown V$ and $\triangle V$. Although the summary-delta V_{SD} in a way also captures the incremental changes to V, using V_{SD} to maintain a higher-level view is much harder than using $\bigtriangledown V$ and $\triangle V$, especially if the higher-level view is not an aggregate view. For this reason, we might prefer SDBATCH as long as it is not significantly slower than the other algorithms.

3.3 Other Issues

3.3.1 Index Maintenance

Like other data warehousing systems, WHIPS creates indexes on warehouse views in order to speed up OLAP queries. Since WHIPS maintains its views incrementally, indexes are also useful for computing maintenance expressions to produce view deltas. On the other hand, indexes on views must be updated whenever the views are updated, so the overhead of index maintenance may degrade the performance of view delta installation. One way to avoid this overhead is to drop all indexes before delta installation and rebuild them afterwards. However, rebuilding the indexes could exceed the cost of maintaining them, and in some cases indexes are useful for delta installation procedures. For example, cursor-based implementations of GenInstall can use an index on the view to quickly locate the view tuples that match a delta tuple (Section 3.1). In Section 4.3, we quantify the tradeoff between rebuilding indexes and maintaining them incrementally during delta installation.

3.3.2 VDAG Maintenance and Compute/Install Ratio

The work of incrementally maintaining a single view can be divided into two phases: a compute phase in which we compute the deltas for the view, and an install phase in which we apply these deltas to the view. (These two phases were first introduced in Section 3.2.3 in the context of SDbatch, but they apply to nearly all view maintenance procedures.) In WHIPS, the warehouse views are organized into a VDAG (Section 2), and maintenance of the VDAG is also divided into two phases. In the first phase, the Warehouse Maintainer performs the compute phase for each derived view in the VDAG, in a bottom-up fashion. That is, if the VDAG contains an edge $V_j \rightarrow V_i$, we compute the deltas for V_i first and then use them to compute the deltas for V_j. (Deltas for base views are provided by the Integrator component, as discussed in Section 2.2.) In the second phase, the Warehouse Maintainer performs delta installation for all views in the VDAG in one transaction. Installing all deltas inside one transaction prevents queries from reading inconsistent warehouse data, and by grouping all delta installation together at the very end of the maintenance procedure, we minimize the duration of this transaction.

The ratio of delta computation time to delta installation time, or *compute/install ratio* for short, is a useful metric that helps us identify performance bottlenecks in warehouse maintenance. For example, a low compute/install ratio might indicate that too much of the maintenance time is spent locking views for update, so we need to focus on fine-tuning delta installation or consider switching to a maintenance strategy that trades the efficiency of the compute phase for the efficiency of the install phase (such as SDbatch in Section 3.2.3). Since the compute/install ratio varies for different types of views, the overall compute/install ratio for an entire VDAG depends on the mix of views in the VDAG. In Section 4.3, we measure the compute/install ratios for both aggregate and non-aggregate views, and discuss how these results affect strategies for further optimizing view maintenance.

4 Experiments

Section 3 introduced the areas in which we must make critical decisions on warehouse view representation and maintenance, and provided some qualitative comparisons of the alternatives. For each decision area, we now quantitatively compare the performance of various alternatives through experiments. The performance results presented in Sections 4.1–4.3 correspond to the decision areas discussed in Sections 3.1–3.3 respectively.

The commercial DBMS we are using is running on a dedicated Windows NT machine with a Pentium II processor.[1] The buffer size is set at 32MB. Recall that the WHIPS Warehouse Maintainer sends a sequence of DML statements to the DBMS to query and update views in the data warehouse. In the experiments, we measure the wall-clock time required for the DBMS to run these DML commands, which represents the bulk of the time spent maintaining the warehouse.

The base views used in the experiments are copies of several TPC-D [TPC96] tables, including fact tables $Order$ and $Lineitem$, which we call O and L for short. The derived views vary from one experiment to the next. Contents of the base views and their deltas are generated by the standard `dbgen` program supplied with the TPC-D benchmark. A TPC-D scale factor of 1.0 means that the entire warehouse is about 1GB in size, with L and O together taking up about 900MB. To limit the duration of repeated experiments, we used relatively small scale factors for the results presented in this section. Of course, to study scalability issues we also have explored wide ranges of scale factors for some of our experiments, and we found the performance trends to be consistent with the results presented.

4.1 View Representation and Delta Installation

In Section 3.1.4 we identified three decisions that need to be made regarding view representation and delta installation: (1) whether to use DUP or CNT as the view representation; (2) whether to use GENINSTALL or KEYINSTALL to install deltas when the view has a key; (3) whether to use a cursor loop or SQL statements to implement GENINSTALL under the CNT representation. In this section, we present performance results that help us make the best decisions for all three areas. The results are presented in reverse order, because we need to choose the best GENINSTALL implementation for CNT (decision area 3) before we can compare CNT with DUP (decision area 1).

4.1.1 GENINSTALL Under CNT: Cursor vs. SQL

In the first experiment, we compare the time to install deltas for base view L^{CNT} (view L using the CNT representation) using a cursor-based implementation versus a SQL-based implementation for GENINSTALL. A TPC-D scale factor of 0.1 is used. Normally, L has a key $\{orderkey, linenumber\}$ and therefore contains no duplicates. For this experiment, however, we artificially introduce duplicates into L so that on average each L tuple has two other duplicates (i.e., L has a *multiplicity* of 3). We also vary the update ratio of L from 1% to 10%. An update ratio of $k\%$ implies $|\bigtriangledown L| = |\triangle L| = (k/100) \cdot |L|$, i.e., $(k/100) \cdot |L|$ tuples are deleted from L and $(k/100) \cdot |L|$ tuples are inserted. Finally, we assume L^{CNT} has an index on $\{orderkey, linenumber\}$. (The effect of indexes on the performance of delta installation will be covered in Section 4.3.1.)

Figure 13 plots the time it takes for the two GENINSTALL implementations to process $\bigtriangledown L$ and $\triangle L$. Recall from Section 3.1 that cursor-based GENINSTALL processes a delta table one tuple at a time, similar to a nested-loop join between the delta and the view with the delta being the outer table. As a result, the plots of cursor-based GENINSTALL for $\bigtriangledown L$ and $\triangle L$ are linear in the size of $\bigtriangledown L$ and $\triangle L$ respectively.

[1]We are not permitted to name the commercial DBMS we are using (nor the second one we are using to corroborate some of our results), but both are state-of-the-art products from major relational DBMS vendors.

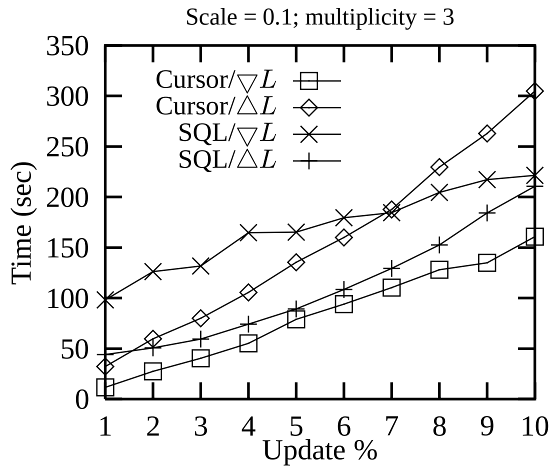

Figure 13: GENINSTALL under CNT.

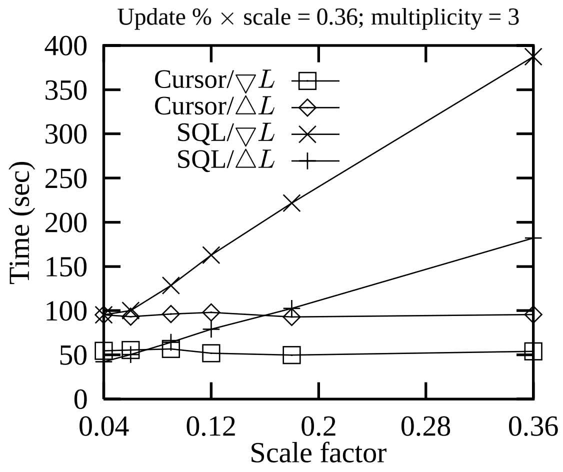

Figure 14: GENINSTALL under CNT.

SQL-based GENINSTALL is optimized by the DBMS. To ensure that the optimizer has access to the most up-to-date statistics, we explicitly ask the DBMS to gather statistics after L, $\bigtriangledown L$, and $\bigtriangleup L$ are populated (and the time spent in gathering statistics is not counted in the delta installation time). If the optimizer were perfect, SQL-based GENINSTALL would never perform any worse than cursor-based GENINSTALL, because the cursor-based plan is but one of the many viable ways to execute SQL-based GENINSTALL. Unfortunately, we see in Figure 13 that SQL-based GENINSTALL is consistently slower than cursor-based GENINSTALL for deletion installation. This phenomenon illustrates the difficulty of optimizing `DELETE` and `UPDATE` statements with correlated subqueries, such as the second `DELETE` statement shown in Section 3.1.2. The way these statements are structured in SQL leads naturally to an execution plan that scans the entire view looking for tuples to delete or update. However, in an incrementally maintained warehouse, deltas are generally much smaller than the view itself, so a better plan is to scan the deltas and delete or update matching tuples in the view, assuming the view is indexed. Evidently, the state-of-the-art commercial DBMS used by WHIPS missed this plan, which explains why the plots for SQL-based GENINSTALL go nowhere near the origin. We expect this behavior may be typical of many commercial DBMS's today, and we have confirmed this expectation by replicating some of our experiments on another major relational DBMS.

On the other hand, the DBMS is more adept at optimizing SQL-based GENINSTALL for insertions, presumably because `INSERT` statements can be optimized similarly to regular `SELECT` queries and more easily than `DELETE` statements. As shown in Figure 13, SQL-based GENINSTALL is faster than cursor-based GENINSTALL for insertion installation when the update ratio is higher than 1%. To summarize, at TPC-D scale factor 0.1 and update ratio between 1% and 10% on the DBMS we are using, cursor-based GENINSTALL is preferred for deletion installation and SQL-based GENINSTALL is preferred for insertion installation under the CNT representation.

In the next experiment, we investigate how the size of the views might affect this decision. We fix the size of $\bigtriangledown L$ and $\bigtriangleup L$ at about 2.6MB each while varying the TPC-D scale factor from 0.04 to 0.36. The update ratio thus varies from 9% to 1%. The results in Figure 14 indicate that the running time of cursor-based GENINSTALL is insensitive to the change in $|L|$, while the running time of SQL-based GENINSTALL grows linearly with $|L|$. Thus, we should use cursor-based GENINSTALL to process both deletions and insertions for large views with low update ratios.

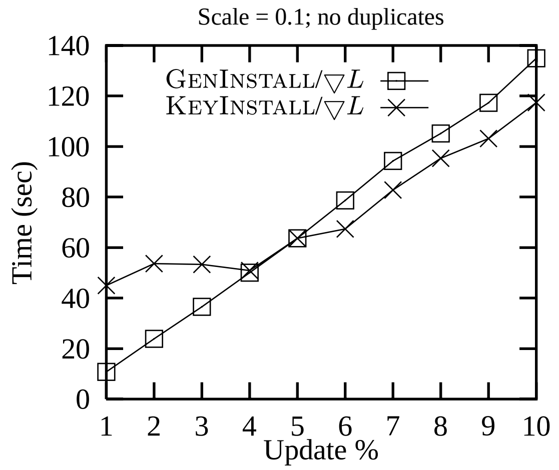

Figure 15: KeyInstall vs. GenInstall under dup.

4.1.2 Delta Installation: KeyInstall vs. GenInstall

In the following experiment, we seek to quantify the performance benefits of using KeyInstall instead of GenInstall when the view has a key and hence no duplicates. In this case, we are only interested in the dup representation since dup should always be used instead of cnt when the view contains no duplicates (Section 3.1.4). Furthermore, under the dup representation, insertion installation requires one simple `INSERT` statement, which is the same for both KeyInstall and GenInstall. Therefore, our task reduces to comparing KeyInstall and GenInstall for deletion installation under the dup representation.

In Figure 15, we plot the time it takes for KeyInstall and GenInstall to install $\bigtriangledown L$ in base view L, which contains no duplicates and has an index on its key attributes. We fix the TPC-D scale factor at 0.1 and vary the update ratio from 1% to 10%. At first glance, the results may seem counterintuitive: KeyInstall is in fact slower than GenInstall when the update ratio is below 5%. However, recall from Section 3.1.2 that KeyInstall uses a simple `DELETE` statement to install $\bigtriangledown L$, while GenInstall requires a cursor loop. Clearly, the DBMS has failed again to take advantage of the small $\bigtriangledown L$ and the index on L when optimizing the `DELETE` statement. Given this limitation of the DBMS optimizer, we cannot justify implementing KeyInstall in addition to GenInstall in the Warehouse Maintainer from a performance perspective.

4.1.3 View Representation: Dup vs. Cnt

We now evaluate the performance of dup and cnt representations in the case where the view may contain duplicates. In Figure 16, we compare the the time it takes to install $\bigtriangledown L$ and $\bigtriangleup L$ under dup and cnt representations. Again, the TPC-D scale factor is fixed at 0.1 and the update ratio varies from 1% to 10%. The multiplicity of L in this first experiment is close to 1, i.e., L contains almost no duplicates. We create indexes for both L^{DUP} and L^{CNT} on $\{orderkey, linenumber\}$, even though $\{orderkey, linenumber\}$ is not a key for L^{DUP} because of potential duplicates. For the cnt representation, we use cursor-based GenInstall to install $\bigtriangledown L^{\text{CNT}}$ and SQL-based GenInstall to install $\bigtriangleup L^{\text{CNT}}$, as decided in Section 4.1.1 for scale factor 0.1. The results plotted in Figure 16 indicate that delta installation (insertions and deletions combined) under the cnt representation is about twice as expensive as delta installation under the dup representation.

In the next experiment, we increase the multiplicity of L from 1 to 3, thereby tripling the size of L^{DUP},

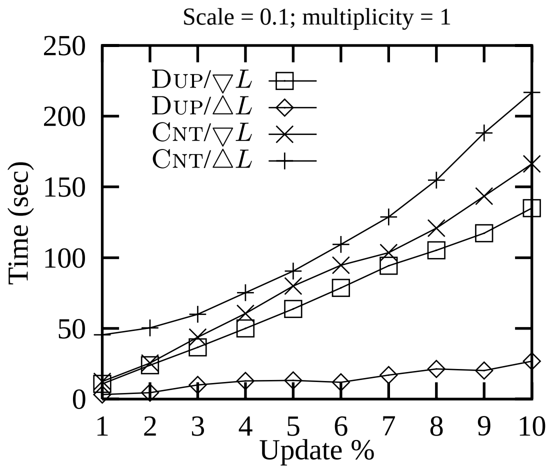

Figure 16: DUP vs. CNT for delta installation.

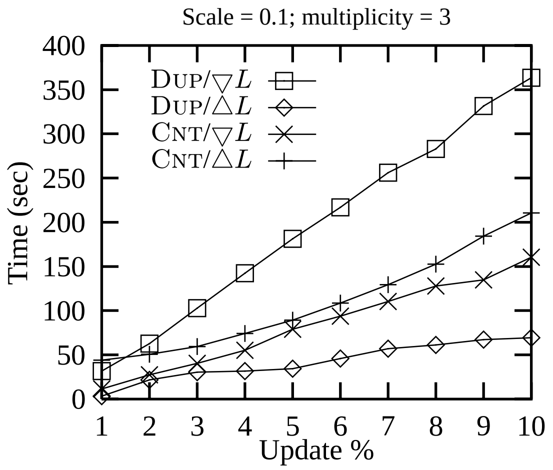

Figure 17: DUP vs. CNT for delta installation.

	DUP representation	CNT representation
$\bigtriangledown$ (deletion)	$1.94\,ms$ / tuple	$\frac{2.49\,ms}{\text{multiplicity}}$ / tuple
$\triangle$ (insertion)	$0.57\,ms$ / tuple	$\frac{4.48\,ms}{\text{multiplicity}}$ / tuple

Table 1: Per-tuple delta installation costs.

$\bigtriangledown L^{\text{DUP}}$, and $\triangle L^{\text{DUP}}$. On the other hand, the increase in multiplicity has no effect on the size of L^{CNT}, $\bigtriangledown L^{\text{CNT}}$, and $\triangle L^{\text{CNT}}$. As Figure 17 shows, installing $\bigtriangledown L^{\text{DUP}}$ becomes more than twice as slow as installing $\bigtriangledown L^{\text{CNT}}$, but installing $\triangle L^{\text{DUP}}$ is still three times faster than installing $\triangle L^{\text{CNT}}$. Overall, delta installation under the DUP representation is slightly slower than under the CNT representation. By comparing Figures 16 and 17, we also see that the delta installation time under the DUP representation increases proportionately with multiplicity, while the time under CNT remains the same.

To study the effect of view size on delta installation time, we conduct another experiment in which we fix the size of the deltas and vary the TPC-D scale factor from 0.04 to 0.36. Multiplicity of L is set at 3. For the CNT representation, we use the best GENINSTALL implementation (either cursor-based or SQL-based, depending on the scale factor; recall Section 4.1.1). The results are shown in Figure 18. Notice that all four plots become nearly flat at large scale factors: when the view is sufficiently large, the cost of installing a delta tuple into the view approaches a constant for each delta type and each view representation. Thus, measured once, these per-tuple costs can be used to estimate the delta installation time in a large data warehouse. Table 1 shows the per-tuple installation costs measured under our experimental settings.

All experiments so far have focused on delta installation. In the next experiment, we compare the time to compute deltas for derived views under DUP and CNT representations. We define one derived view LO_1 as an equijoin between L and O, with a total of 24 attributes. Another derived view LO_2 is defined as the same equijoin followed by a projection which leaves only two attributes. In Figure 19, we plot the the time it takes to compute $\bigtriangledown LO_1$ and $\bigtriangledown LO_2$ given $\bigtriangledown L$ under both DUP and CNT representations. We choose an update ratio of 5% and increase the multiplicity of L from 1 to 5. When the multiplicity of L is close to 1 (i.e., L contains almost no duplicates), DUP and CNT offer comparable performance for computing derived view deltas. The overhead of the extra *dupcnt* attribute and the extra aggregation required for doing projection under the CNT representation (discussed in Section 3.1.1) turns out to be insignificant in this case. As we increase the multiplicity, computing derived view deltas under DUP becomes progressively slower than CNT

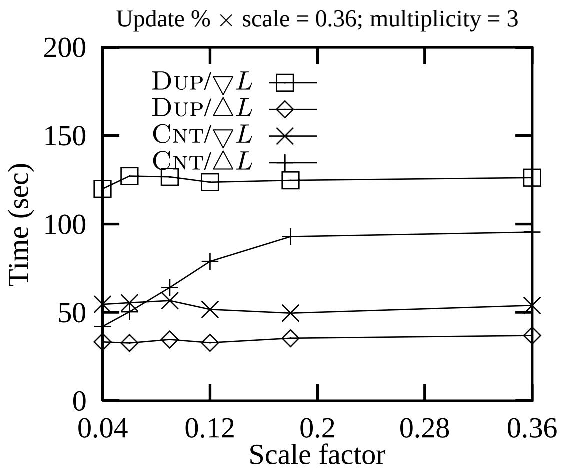

Figure 18: DUP vs. CNT for delta installation.

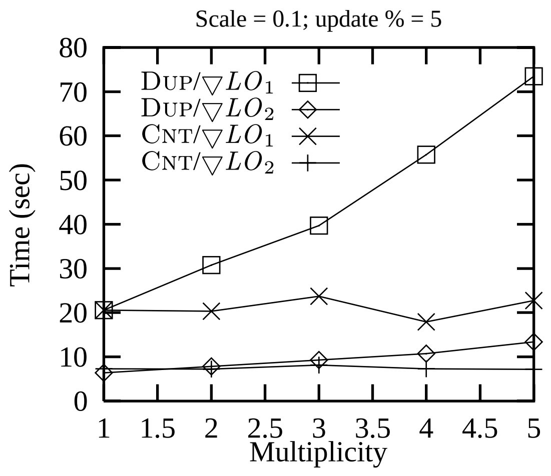

Figure 19: DUP vs. CNT for delta computation.

because the CNT representation is about m times more compact than DUP, where m is the multiplicity.

To summarize, the CNT representation scales well with increasing multiplicity and carries little overhead for computing derived view deltas. However, in the common case where the average number of duplicates is low (e.g., multiplicity is less than 3), the DUP representation is preferable because it is faster in installing deltas, especially insertions, which tend to be the most common type of changes in data warehousing applications.

4.2 Maintaining Aggregate Views

In Section 3.2 we presented aggregate view maintenance algorithms FULLRECOMP and SDCURSOR, as well as two new variations SDBATCH and SDOVERWRITE. This section compares the performance of the four algorithms in terms of the total time required for maintaining aggregate views. We also compare the install phase lengths of SDCURSOR and SDBATCH. Recall from Section 3.2.5 that we want to minimize the length of the install phase in a data warehouse because during this phase the view is locked for update.

We consider two types of aggregate views in our experiments. A *fixed-ratio* aggregate over a base view V groups V into $\alpha \cdot |V|$ groups, where α is a fixed *aggregation ratio*. The size of a fixed-ratio aggregate increases with the size of the base view. On the other hand, a *fixed-size* aggregate over a base view V groups V into a small and fixed number of groups. We will see that the four aggregate maintenance algorithms behave differently for these two types of aggregates.

4.2.1 Maintaining Fixed-Ratio Aggregates

In the first experiment, we use a fixed-ratio aggregate V_{large} which groups the base view L by $orderkey$ into approximately $0.25 \cdot |L|$ groups. First, we study the impact of the update ratio on the maintenance time of V_{large} by fixing the TPC-D scale factor at 0.1 and varying the update ratio from 1% to 10%. Figure 20 shows that the update ratio has no effect on FULLRECOMP at all. However, the total maintenance time increases (gradually) with the update ratio for the three summary-delta-based algorithms. Among these algorithms, SDCURSOR is most sensitive to the change in update ratio, and SDOVERWRITE is least sensitive. Figure 20 also shows that FULLRECOMP is far more expensive that the other three algorithms. SDBATCH is the fastest when the update ratio is small, while SDOVERWRITE becomes the fastest when the update ratio is

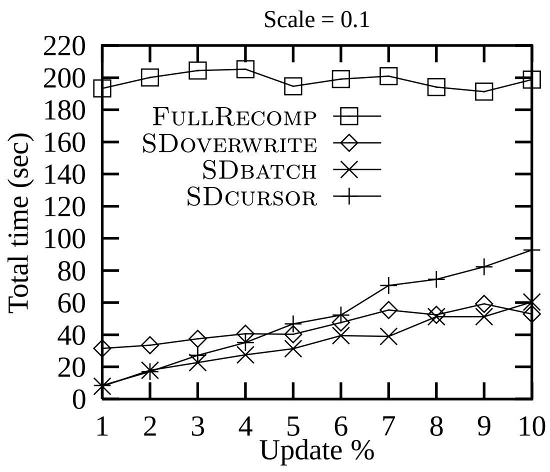

Figure 20: Maintaining V_{large}.

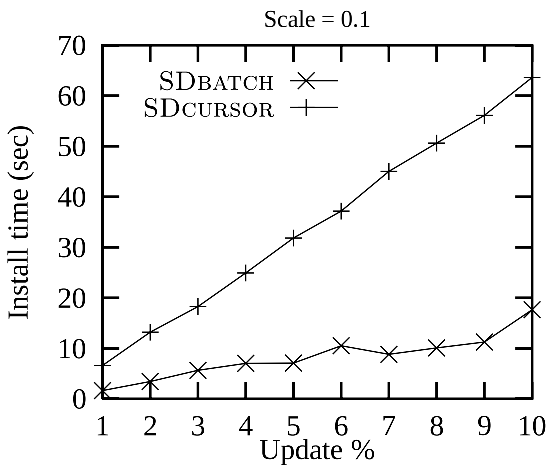

Figure 21: Installing deltas for V_{large}.

higher than 10%. In Figure 21, we further compare SDcursor and SDbatch in terms of the time of the install phase. By doing more work in its compute phase, SDbatch has a much shorter install phase than SDcursor. This shorter install phase gives our new algorithm SDbatch an edge in applications where data availability is important.

To study the impact of base view size on aggregate maintenance, we fix the size of $\bigtriangledown L$ and $\triangle L$ and vary the scale factor of L from 0.04 to 0.36. Figure 22 shows that the performance of FullRecomp deteriorates dramatically as $|L|$ increases, because FullRecomp is recomputing the aggregate over a larger L. Although SDoverwrite and SDbatch are not affected by $|L|$ as much as FullRecomp, their running time still increases because $|V_{large}|$ grows with $|L|$. On the other hand, SDcursor is almost unaffected by the increase in $|L|$. The reason is that SDcursor uses an index on V_{large} to find the matching V_{large} tuples for each tuple in the summary-delta table, and the lookup time of the index remains constant for the range of $|V_{large}|$ in this experiment. Figure 22 also shows that FullRecomp is much slower than the other algorithms. SDbatch is the fastest algorithm for smaller base views, while SDcursor is the fastest for larger base views.

Figure 23 further compares the time of the install phase for SDcursor and SDbatch. The install phase of SDcursor is not affected by the size of the base view, for the same reason discussed above. The install phase of SDbatch takes much less time than that of SDcursor for relatively small base views, but it increases as the base view becomes larger. Once again, the explanation lies with the limitation of the DBMS optimizer. When executing the SQL `DELETE` statement to install $\bigtriangledown V_{large}$, the DBMS fails to make use of the available index on V_{large}; instead, it scans V_{large} looking for tuples to delete, which requires time proportional to $|V_{large}|$, or $0.25 \cdot |L|$.

4.2.2 Maintaining Fixed-Size Aggregates

We now compare the performance of the four algorithms for a fixed-size aggregate view V_{small}, which groups the base view L by *linenumber* into exactly seven groups, regardless of the size of L. Figure 24 shows the impact of the update ratio on the maintenance of V_{small}. Again, the performance of FullRecomp does not change much as the update ratio increases. Plots of the other three algorithms, although somewhat noisy due to inconsistent DBMS behavior, show that the total maintenance time increases at about the same rate for all three algorithms. The reason is that the time it takes to compute the summary-delta ta-

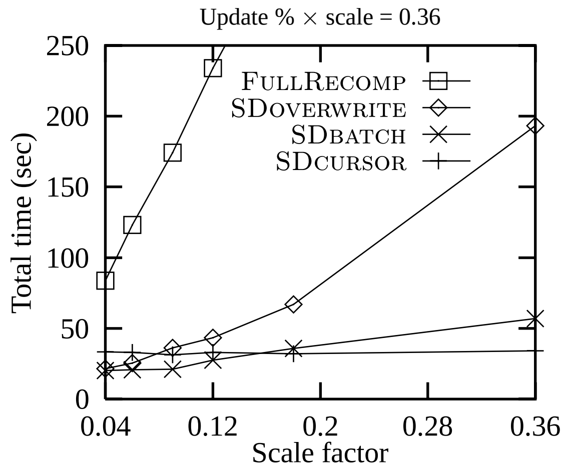

Figure 22: Maintaining V_{large}.

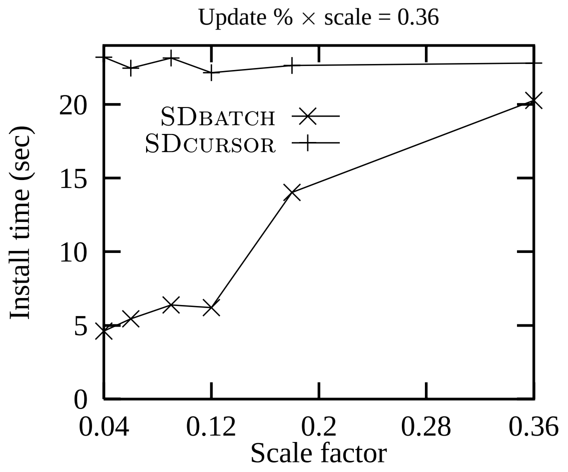

Figure 23: Installing deltas for V_{large}.

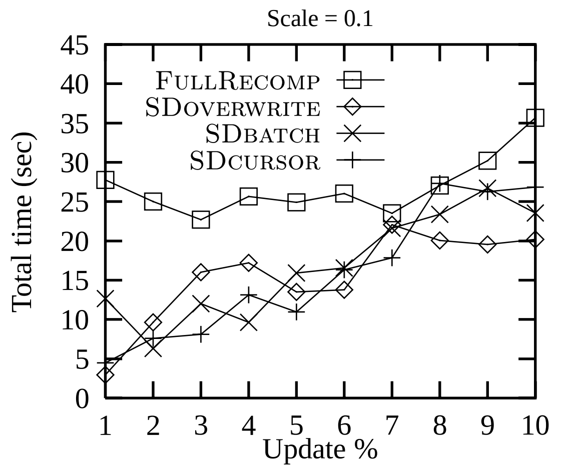

Figure 24: Maintaining V_{small}.

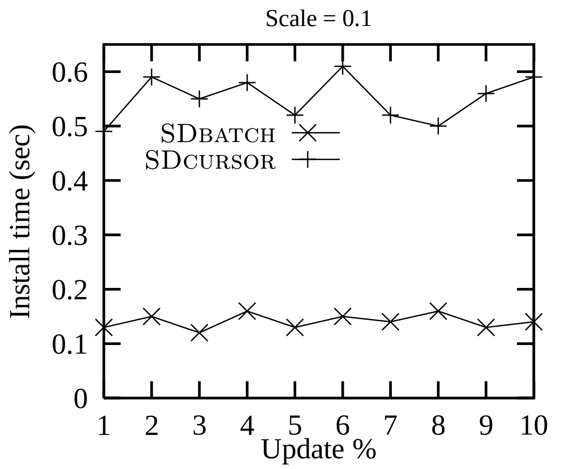

Figure 25: Installing deltas for V_{small}.

ble (which is used by all three algorithms) increases with the update ratio. On the other hand, the size of the summary-delta is usually fixed for a small fixed-size aggregate such as V_{small}, because any base view delta of reasonable size will likely affect all groups in the aggregate. The type of work after computing the summary-delta varies from one algorithm to another, but for each algorithm, the amount of work depends only on the size of the aggregate and the size of the summary-delta, which are both fixed in this case. Figure 25 further indicates that SDbatch has a shorter install phase than SDcursor, and neither is affected by the update ratio because V_{small} is a fixed-size aggregate. In this case the install phase does not take a significant portion of the total maintenance time, but as we have discussed, the length of the install phase is still an important measure of warehouse availability.

Finally, Figures 26 and 27 plot the total maintenance time and installation time of V_{small} respectively as we fix the size of the base view deltas and vary the size of the base view. We see in Figure 26 that FullRecomp becomes dramatically slower as the base view becomes larger. However, the other three algorithms are not affected, again because the size of the aggregate and the size of the summary-delta remain constant despite the increasing base view size. Figure 27 also shows that the install phase of SDcursor and SDbatch is not affected by the increasing base view size. Furthermore, SDbatch has a faster install phase than SDcursor.

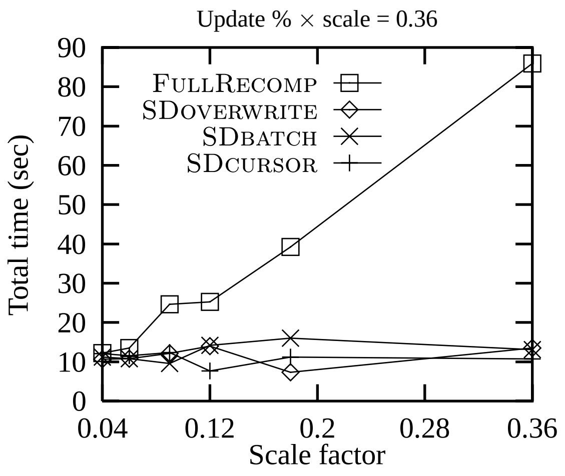

Figure 26: Maintaining V_{small}.

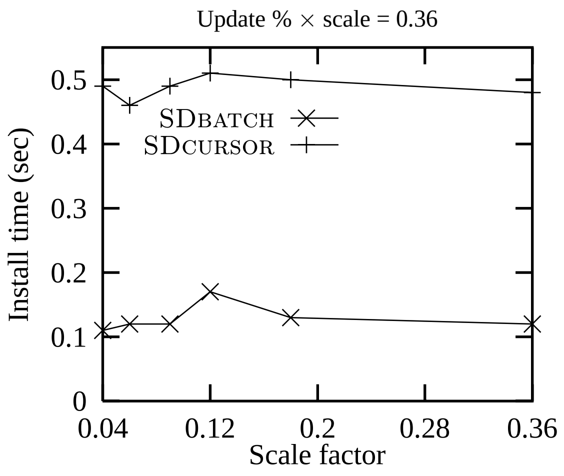

Figure 27: Installing deltas for V_{small}.

	fixed-ratio aggregate		fixed-size aggregate	
	base view delta size	base view size	base view delta size	base view size
FullRecomp	0	3	0	3
SDoverwrite	1	2	1	0
SDbatch	2	1	1	0
SDcursor	3	0	1	0

Table 2: Sensitivity of aggregate view maintenance algorithms.

4.2.3 Summary

Based on our experiments, we learn that the aggregate maintenance algorithms behave differently on different types of aggregate views. In addition, two other factors—the size of the base view and the size of the base view deltas—also affect the performance of aggregate view maintenance, and different maintenance algorithms react differently to these factors. Table 2 summarizes the sensitivity of each algorithm to various factors using a scale of 0 (insensitive) to 3 (very sensitive).

In conclusion, the following guidelines may be used to choose an aggregate view maintenance algorithm for a given scenario:

- Algorithms based on summary-delta tables (SDbatch, SDcursor, and SDoverwrite) are much faster than FullRecomp, especially for relatively large base views.

- For fixed-ratio aggregates, SDcursor is preferred for large base views with small deltas, while SDoverwrite is preferred for small base views with large deltas. SDbatch is a compromise between the two.

- For fixed-size aggregates, all three algorithms based on summary-delta tables perform equally well.

- SDbatch generally has a shorter install phase than SDcursor. However, in the case of fixed-ratio aggregates this advantage of SDbatch could diminish as the size of the base view increases if the DBMS is unable to optimize `DELETE` statements effectively.

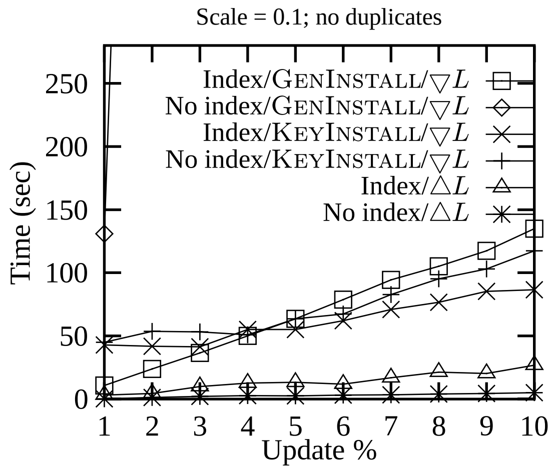

Figure 28: Effect of index on delta installation.

4.3 Other Issues

4.3.1 Index Maintenance

All experiments presented so far have used indexes on the views, and these indexes were maintained incrementally together with the views. In the next experiment, we measure the overhead of index maintenance in delta installation by comparing the time it takes to install $\bigtriangledown L$ and $\bigtriangleup L$ with and without an index. We use the DUP representation for L and assume that L contains no duplicates, so we build the index on key attributes $\{orderkey, linenumber\}$. The TPC-D scale factor is 0.1 and the update ratio varies from 1% to 10%. To determine the impact of the index on different delta installation strategies, we measure the time to install $\bigtriangledown L$ using both SQL-based KeyInstall and cursor-based GenInstall. On the other hand, $\bigtriangleup L$ is always installed using one simple `INSERT` statement.

From the results shown in Figure 28, we see that installing $\bigtriangledown L$ using KeyInstall and installing $\bigtriangleup L$ are both slower with the index. The total overhead of index maintenance increases from 5 to 53 seconds as the update ratio increases from 1% to 10%. Rebuilding the index on L takes about 50 seconds. Therefore, rebuilding the index after delta installation is better than maintaining the index incrementally only for high update ratios. Figure 28 also shows that installing $\bigtriangledown L$ using GenInstall is significantly slower without the index (so slow that we had to truncate its plot in order to show the other plots clearly). This huge disparity clearly outweighs the cost of index maintenance. We expect all cursor-based delta installation procedures to perform poorly without the index because they rely on the index to quickly find matching view tuples for each delta tuple.

In conclusion, if all delta installation procedures are SQL-based and the update ratio is high, we should consider dropping the index during delta installation and rebuilding it afterwards. Otherwise, keeping the index and maintaining it during delta installation leads to better performance.

4.3.2 Compute/Install Ratio

Recall that the view maintenance process is divided into two phases: a compute phase which computes the view deltas, and an install phase which applies the deltas to the view. In this section, we compare the amount of time spent on each phase using the compute/install ratio as a metric. In the following set of experiments,

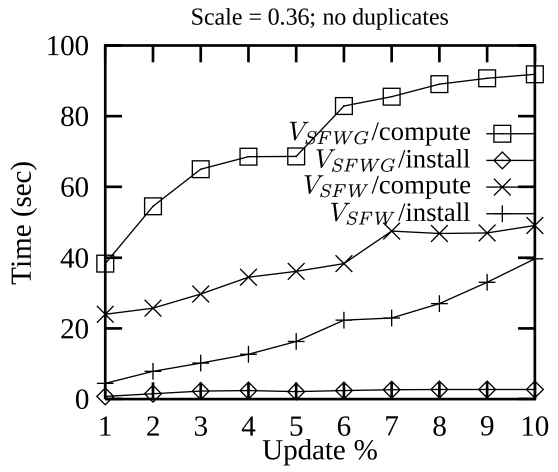

Figure 29: Maintaining V_{SFWG} and V_{SFW}.

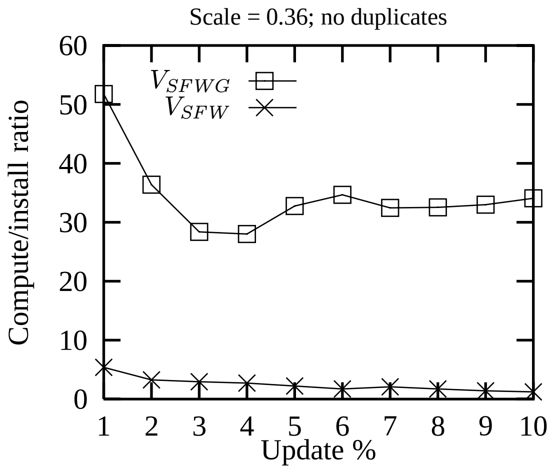

Figure 30: Compute/install ratio for V_{SFWG} and V_{SFW}.

we consider two derived views V_{SFWG} and V_{SFW} of different types. V_{SFWG} is a SQL SFWG view defined by query Q_{10} in the TPC-D benchmark, which is an aggregate over a join of four base views including fact table L. V_{SFW} is a SQL SFW view similar to V_{SFWG}, except that it projects away more attributes and has no aggregation. We use SDBATCH to maintain V_{SFWG}, and we use standard maintenance expressions and KEYINSTALL to maintain V_{SFW}.

We first study the impact of the update ratio on the compute/install ratio by fixing the TPC-D scale factor at 0.36 and varying the update ratio from 1% to 10%. Figure 29 shows the computation time and installation time for both V_{SFWG} and V_{SFW}. We see that V_{SFWG}, an aggregate view, has a longer compute phase but a shorter install phase than V_{SFW}. Therefore, the compute/install ratio of V_{SFWG} is much higher than that of V_{SFW}, as shown in Figure 30. Notice that the compute/install ratio of V_{SFW} decreases as the update ratio increases, while the compute/install ratio of V_{SFWG} becomes fairly stable once the update ratio reaches 3%.

To study the impact of the base view size on the compute/install ratio, we fix the size of the deltas and increase the scale factor of the base views from 0.04 to 0.36. Figure 31 shows the computation time and installation time for both views, and Figure 32 shows their compute/install ratios. As the the base views get bigger, the compute/install ratio of V_{SFW} remains fairly low, while the compute/install ratio of V_{SFWG} increases dramatically.

To summarize, several factors can affect the compute/install ratio of a derived view, including the view definition, the base view size, the base view delta size, and the algorithm used for view maintenance. In general, an aggregate derived view maintained using SDBATCH typically has a large compute/install ratio, while a non-aggregate derived view has a relatively small ratio. Therefore, to further improve the performance of view maintenance, we should focus our efforts on fine-tuning the compute phase for aggregate views and the install phase for non-aggregate views. Overall, the compute/install ratio for an entire VDAG depends on the mix of views in the VDAG.

5 Related Work

There has been a significant amount of research devoted to view maintenance; see [GM95] for a survey. However, there has been little coverage of the important details of view maintenance that are the focus of

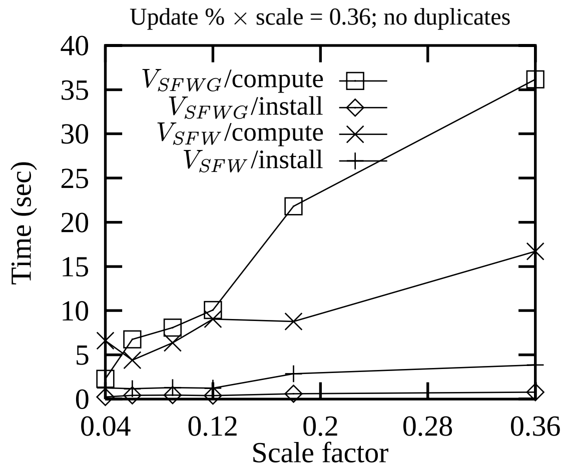

Figure 31: Maintaining V_{SFWG} and V_{SFW}.

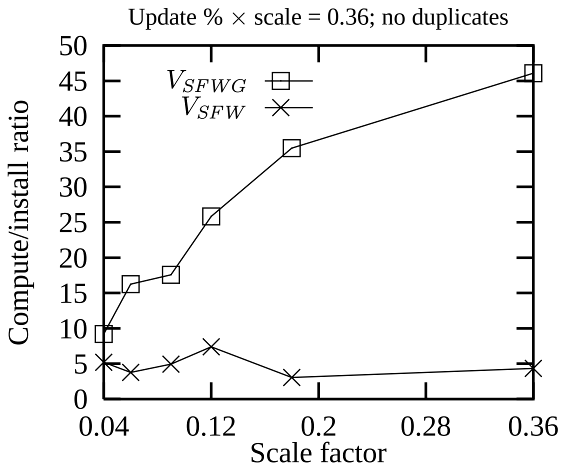

Figure 32: Compute/install ratio for V_{SFWG} and V_{SFW}.

this paper. For instance, [LYGM99] assumes that there is an *Inst* operation for installing deltas into a view, but does not cover the details on how to implement *Inst*. [MQM97] proposes the summary-delta algorithm for aggregate maintenance, but does not consider the various alternatives for applying the summary delta to the aggregate view. In this paper, we have presented three possible implementations of the view maintenance procedure, and evaluated their performance through experiments.

[GMS93] assumes that materialized views use the CNT representation. On the other hand, [GL95] assumes that the DUP representation is used. To our knowledge, our paper is the first to investigate in detail the pros and cons of the two representations for view maintenance, and to present supporting experiments.

We also briefly described the WHIPS data warehousing system. Although significant research has been devoted to both view maintenance and data warehousing, few warehouse prototypes focus on incremental view maintenance the way WHIPS does. [HZ96] presents the *Squirrel* integration mediator, which acts as a data warehouse. [HZ96] focuses on support for virtual attributes in warehouse views, but does not discuss the details of view maintenance in Squirrel.

[GHJ96] describes the *Heraclitus* project, in which deltas are treated as first-class citizens in a database programming language. [GHJ96] does not permit duplicates, and it proposes hash-based and sort-merge-based delta installation procedures. In this paper, we also consider the general case where the views may contain duplicates, and we propose cursor-based delta installation procedures to exploit the indexes that typically exist on warehouse views.

[CKL$^+$97] presents the *Sword* warehouse prototype, which supports multiple view maintenance policies specifying when to maintain the warehouse views (e.g., immediately versus on-demand). [CKL$^+$97] studies the performance tradeoffs between the different view maintenance policies. The results presented in our paper can be used to optimize the actual implementation of each maintenance policy; thus, our results are complementary to [CKL$^+$97].

[Rou91] describes the *ADMS* prototype, which investigates the advantages of materializing a view using *view-caches* (join indexes) as opposed to view tuples. Commercial DBMS's currently do not allow materialized views to be represented using join indexes. Therefore, a data warehousing system such as WHIPS that is implemented using a commercial DBMS must use actual view tuples.

[Vis98] presents *RHODES*, a query optimizer designed for view maintenance, built using the Volcano optimizer generator [GM93]. [Vis98] focuses on optimizing delta computation for SFW views and not on optimizing delta installation. Our results show that delta installation takes a substantial fraction of warehouse maintenance time and therefore warrants the careful study presented in this paper.

As mentioned in Section 1, incremental warehouse maintenance has also found its way into commercial systems, such as the Red Brick database loader [FS96], Oracle materialized views [BDD$^+$98], and DB2 automatic summary tables [BS99]. The results in this paper should be especially useful to the vendors for improving the performance of these systems, since we have conducted all our experiments on a commercial DBMS as well.

6 Conclusion

This paper has addressed performance issues in incrementally maintained data warehouses, with our own WHIPS prototype serving as a framework for experimenting with new techniques for efficient view maintenance. We identified several critical data representation and algorithmic decisions, and proposed guidelines for making the right decisions in different scenarios, supported by our experimental results. From the results of our experiments, we can see that making the right decision requires considerable analysis and tuning, because the optimal strategy often depends on many factors such as the size of views, the size of deltas, and the average number of duplicates. Ideally, some of the decisions can and should be made by the DBMS optimizer, since it has access to most relevant statistics. However, because of current limitations of DBMS optimizers, many decisions still need to be made by an external agent, such as the Warehouse Maintainer in WHIPS or a human warehouse administrator. As DBMS vendors continue to introduce more data warehousing features, we hope that view maintenance, especially delta installation, will receive an increasing level of support.

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