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Materialized Views

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Abstract

Materialized views are queries whose results are stored and maintained in order to facilitate access to data in their underlying base tables. In the SQL setting, they are now considered a mature technology implemented by most commercial database systems and tightly integrated into query optimization. They have also helped lay the foundation for important topics such as information integration and data warehousing. This monograph provides an introduction and reference to materialized views. We cover three fundamental problems: (1) maintaining materialized views efficiently when the base tables change, (2) using materialized views effectively to improve performance and availability, and (3) selecting which views to materialize. We also point out their connections to a few other areas in database research, illustrate the benefit of cross-pollination of ideas with these areas, and identify several directions for research on materialized views.

Contents

1

Introduction

Materialized views are a natural embodiment of the ideas of *precomputation* and *caching* in databases. Instead of computing a query from scratch from base data, a database system can use results that have already been computed, stored, and maintained. The ability of materialized views to speed up queries benefit most database applications, ranging from traditional querying and reporting to web database caching [255], online analytical processing [89], and data mining [208, 367]. By reducing dependency on the availability of base data, materialized views have also laid much of the foundation for information integration [45, 139, 270] and data warehousing [89, 242] systems. Because of their wide applicability, materialized views are a well-studied topic with both a rich research literature and mature commercial implementations. Our goal of this monograph is to provide an accessible introduction and reference to this topic, explain its core ideas, highlight its recent developments, and point out its sometimes subtle connections to other research topics in databases.

Background A database *view* is defined by a query. When evaluated, this *view definition query* returns the contents of the view. Database

users can pose queries or define other views over views just as they can over regular database tables. Conceptually, when the database system executes a query involving views, references to views are replaced by their definition queries (recursively, if a view is defined using other views), yielding a final query involving only regular "base tables."

Example 1.1 (Adapted from [188]). Consider a retailer with multiple stores across the globe. The stores are grouped into multiple geographic regions for administrative and accounting purposes. The retailer consolidates its inventory and sales information across all stores into a single relational database for auditing and analysis purposes. Consider some of the tables in such a database and their cardinality:

- `pos(itemID, storeID, date, qty, price)`, with one billion (10^9) rows, records point-of-sale transactions. There is one row for every item sold in a transaction, with the ID of item, the ID of the store selling it, the date of sale, the quantity sold, and the unit price.
- `stores(storeID, city, region)`, with 100 rows, records information about each store: namely, its ID, city, and region.
- `items(itemID, name, category, cost)`, with 50,000 rows, records information about each item: namely, its ID, name, product category, and cost per unit.

The following view, defined over `pos`, computes the total sales revenue generated for each item by each store:

```
CREATE VIEW TotalByItemStore(itemID,storeID,total) AS
  SELECT itemID, storeID, SUM(qty*price)
  FROM pos GROUP BY itemID, storeID;
```

Suppose a business analyst wants to know the total revenue generated by each store for each item category. This query can be written against the above view as:

```
SELECT storeID, category, SUM(total)                -- (Q1v)
FROM TotalByItemStore, items
```

```
WHERE TotalByItemStore.itemID = items.itemID
GROUP BY storeID, category;
```

When evaluating this query, the database system conceptually expands it to the following equivalent query involving only base tables:

```
SELECT storeID, category, SUM(qty*price)            -- (Q1)
FROM pos, items
WHERE pos.itemID = items.itemID
GROUP BY storeID, category;
```

Traditionally, views are "virtual" — the database system stores their definition queries but not their contents. Virtual views are often used to control access and provide alternative interfaces to base tables. They also support *logical data independence*: when the base table schema changes, views can be redefined to use the new schema, so application queries written against these views will continue to function.

Over the years, however, the concept and practice of *materialized views* have steadily gained importance. We materialize a view by storing its contents (though many cases call for alternative materialization strategies; see Section 2.3). Once materialized, a view can facilitate queries that use it (or can be rewritten to use it), when the base tables are expensive or even unavailable for access.

Example 1.2. Continuing with Example 1.1, suppose we materialize the view `TotalByItemStore`. Now, query `(Q1v)` can be evaluated by joining `items` with the materialized contents of `TotalByItemStore`. This evaluation strategy is more efficient than joining `items` and `pos`, because `TotalByItemStore` has up to $50{,}000 \times 100 = 5 \times 10^6$ rows, compared with 10^9 rows in `pos`.

Although `(Q1)` is not originally written over `TotalByItemStore`, it is possible to recognize that `(Q1)` can be rewritten as `(Q1v)` to take advantage of the materialized `TotalByItemStore`.

Key Problems Example 1.2 above illustrates one important question in the study of materialized views: how to *answer queries using views*, especially when the queries are not originally written in terms of the materialized views. The next natural question is, given a database workload (queries and modifications) as well as resource and performance requirements, how to *select what views to materialize* in the first place. Instead of relying on database administrators and application developers to answer these questions in an ad hoc fashion, we prefer a more systematic and automatic approach.

Materialized views are not free. Not only do they take additional space, but they also require maintenance: as base tables change, the materialized view contents become outdated. Thus, a third important question is how to *maintain materialized views* to keep them up to date with respect to the base tables. The most straightforward way to maintain a materialized view is to recompute its definition query over the new database state whenever the base tables change. However, in practice, since the numbers of rows changed are often small compared with the sizes of the entire base tables, *incremental view maintenance* — the practice of computing and applying only incremental changes to materialized views induced by base table changes — may work better than recomputation.

Example 1.3. Continuing with Examples 1.1 and 1.2, suppose that five rows have been inserted into base table `pos` as the result of a sale transaction δ involving five different items at a particular store. Recomputing the materialized view `TotalByItemStore` from scratch would be both unnecessary and expensive, because most of its 5×10^6 rows are not affected by δ. With incremental maintenance, loosely speaking, we only need to identify the five affected rows in `TotalByItemStore` and increment their `total` by `qty*price` of their corresponding new `pos` rows inserted by δ.

To recap, the examples above reveal three key problems concerning materialized views: how to maintain them (*view maintenance*), how to use them (*answering queries using views*), and how to select them (*view*

selection). Solutions and techniques developed for these questions over the years have made materialized views an indispensable technology that greatly enhances the performance and features of database systems and many data-intensive applications, such as those mentioned in the opening of this section. Most commercial database systems now offer built-in support of materialized views; for other systems there exist popular recipes for "simulating" support of materialized views.

The ideas underlying materialized views are simple: e.g., precomputation, caching, and incremental evaluation. However, the great database tradition of *declarative querying* is what distinguishes materialized views from generic applications of these ideas in other contexts, and makes materialized views especially interesting, powerful, and challenging at the same time. Thanks to standardized, declarative database languages with clean semantics, study of materialized views has generated a rich body of theory and practice, aimed at providing efficient, effective, automated, and general solutions to the three key problems above.

Scope and Organization There is a vast body of literature on materialized views dating back to 1980s, not to mention work related to or influenced by it. There have also been other authoritative references to the topic, most notably the 1999 book edited by Gupta and Mumick [188], the 2001 survey by Halevy [203] on answering queries using views, as well as relevant entries in the recently compiled *Encyclopedia of Database Systems* [291]. We intend this monograph to serve as an accessible introduction and reference to the topic of materialized views for database researchers. In addition to covering the core ideas behind materialized views, we will highlight recent developments (especially those since 2000), and discuss connections to other more recent research topics in databases. This monograph is a more of a pedagogical text than a manual: given a problem, instead of presenting one definitive solution (which in many cases may not be clear or even exist), we walk the readers through the line of reasoning and research developments leading to better understanding of the problem. Therefore, this monograph should be used as a companion to, rather than a substitute for, the literature on materialized views.

The breadth of work on materialized views is as daunting as its depth. Different data models and query languages — object-oriented, semistructured, spatiotemporal, streaming, probabilistic, just to name a few — give rise to a multitude of problem settings that sometimes call for specialized techniques. To make this monograph approachable and focused, we limit its scope mostly to nonrecursive SQL views; we also assume that readers are familiar with relational and bag algebras (see standard database textbooks such as [159, 335], or, for quick reference, [370] and [174], respectively). Our hope is that the core ideas we cover will help readers in further exploring other problem settings.

As mentioned earlier, materialized views now have mature implementations in most commercial database systems. In fact, the database industry has contributed significantly — in many cases as leaders — to the research literature. Written primarily with a research audience in mind, this monograph focuses on the research literature (including contributions from the industry) rather than the product specifics. While we give a high-level overview of commercial implementations, we offer no in-depth comparison of product features.

We note that materialized views are but one form of *derived data* — the result of applying some transformation, structural or computational, to base data. The use of derived data to facilitate access to base data is a recurring theme in computer science. Besides materialized views, other examples include caches, replicas, indexes, and synopses [16, 123]. Despite differences in the form, complexity, and precision of derived data, the three fundamental questions remain: how to use derived data, what to maintain as derived data, and how to maintain them. Oftentimes, ideas and techniques developed for one form of derived data can be adapted and applied to another setting with interesting benefits. The repertoire of techniques for materialized views has been enriched by ideas from other forms of derived data. At the same time, many research areas, old and new alike, have drawn insights from materialized views, implicitly or explicitly. This monograph will highlight a few examples of such cross-pollination.

In the remainder of this monograph, Section 2 covers the *view maintenance* problem. Section 3 covers the *view use* problem. Section 4

covers the *view selection* problem. Section 5 explores connections between materialized views and a few other topics. Section 6 concludes with our perspectives on the current state and future directions of the study of materialized views.

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