Virtual Lightweight Snapshots for Consistent Analytics in NoSQL Stores

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***Abstract*—Increasingly, applications that deal with big data need to run analytics concurrently with updates. But bridging the gap between big and fast data is challenging: most of these applications require analytics' results that are fresh and consistent, but without impacting system latency and throughput. We propose *virtual lightweight snapshots* (VLS), a mechanism that enables consistent analytics without blocking incoming updates in NoSQL stores. VLS requires neither native support for database versioning nor a transaction manager. Besides, it is storage-efficient, keeping additional versions of records only when needed to guarantee consistency, and sharing versions across multiple concurrent snapshots. We describe an implementation of VLS in MongoDB and present a detailed experimental evaluation which shows that it supports consistency for analytics with small impact on query evaluation time, update throughput, and latency.**

I. Introduction

The ability to leverage insights from large volumes of rapidly-evolving data is a requirement in an increasing number of applications. Decisions must be made on-the-spot for a given incoming event, but, often, these decisions must also consider large volumes of historical data. Big data companies have acknowledged the need to effectively combine *big data*, i.e., analytics over retrospective data, with *fast data*, i.e., data that is constantly updated, for a wide range of problems, including query suggestion [1] and gift recommendation [2].

At IBM, a middleware called Operational Decision Manager Insights[1] (ODM Insights) has been developed as a foundation for such applications. Figure 1 depicts its architecture. An event processor receives multiple events that reflect on updates to the system's NoSQL data store; simultaneously, it generates actions in response to these events by performing analytics over the same store to analyze historical data and discover new insights. Real-world scenarios that are often addressed by ODM Insights include, but are not limited to, customer payment verification (e.g., detecting promotions and fraudulent activites), air traffic control (e.g., rerouting the closest flights to an airport), and health costumer care (e.g., predicting outbreaks and illness diagnosis). For most of these applications, *data freshness* is crucial, since incorrect decisions may be taken if analytics do not see a recent version of the data. But freshness is not the only concern: analytics results must also reflect a *consistent* view of the data. In these high-stake domains, a seemingly small change in the data can lead to radically different outcomes, and consistency is essential to ensure the integrity of results and predictability of the system's behavior.

Traditionally, update operations (OLTP) and analytics (OLAP) have been handled by different systems. Transactional systems are optimized to support large number of concurrent updates, maximizing throughput and ensuring low latency. In contrast, OLAP systems, such as data warehouses, are optimized for long-running queries that involve expensive table scans. Although changes can be propagated from the transactional store to the data warehouse periodically, analytics end up being performed over an outdated version of the data. Using a single system for both workloads brings freshness to analytics, but leads to resource contention: analytics may hold long-running locks, thus negatively impacting update throughput and latency. To mitigate this problem, a lower level of isolation, such as cursor stability [3], can be used, but this has the undesirable effect that records may change while analytics are in progress, leading to inconsistent results.

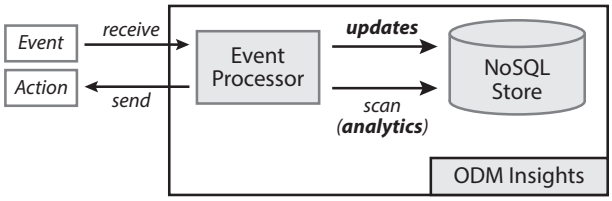


Fig. 1: The ODM Insights middleware for events and analytics.

In the context of the ODM Insights middleware, ensuring consistency is more challenging because the data must reside in a NoSQL system. These systems have been widely used to handle both big and fast data, but they often do so without guaranteeing consistent results. One of the goals for ODM Insights is to support MongoDB as its data store for various reasons [4], including (i) its support to JSON, which brings interoperability and flexibility for the middleware, (ii) its ability to handle high update throughputs, (iii) its implementation of a non-versioned store that limits space requirements, (iv) its popularity, and (v) its availability on IBM's Bluemix cloud platform. However, as many NoSQL systems, MongoDB lacks transactional capabilities and only guarantees weaker forms of consistency, such as atomicity on single record operations and cursor stability for queries. Indeed, despite the foregoing benefits, our prior work with ODM Insights could not use MongoDB directly due to its lack of consistency [4].

This paper introduces ***virtual lightweight snapshots*** (`VLS`), a new snapshotting technique that provides consistency for analytics in the presence of concurrent updates in disk-resident NoSQL systems. `VLS` was designed to require neither a transaction manager nor native support for versioning: snapshots are *virtual* and *built on demand*–as needed by ad-hoc queries–*at a low cost*, having negligible overheads both in terms of latency and throughput. Our approach focuses on non-distributed scenarios (which are common for many ODM

[1] http://ibm.co/1GoqCBy

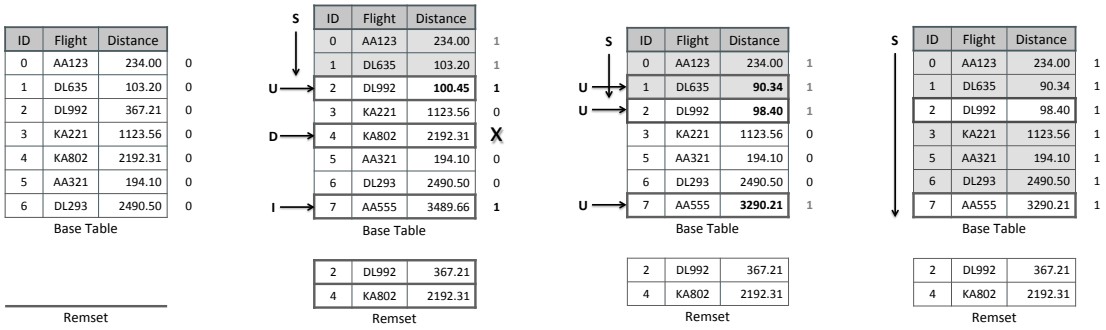


Fig. 2: Single-snapshot approach over the flight table.

Insights use scenarios), but we are extending the solution to address distributed cases as well (see Section VI).

The design of VLS was inspired by concurrent garbage collection (CGC) algorithms, which perform memory reclamation while applications concurrently modify the memory [5]; in a database system, this is equivalent to supporting a query to execute over a consistent snapshot while updates are taking place. Therefore, VLS can be seen as a snapshot isolation technique [6] that is amenable for implementation in NoSQL stores. Our approach also shares some similarities with previous work on *transient versioning* [7]–[9], in the sense that snapshots are created on demand. There is, however, an important difference: VLS does not require a transaction manager. This is key to the applicability of VLS to ODM Insights, as many NoSQL systems, including MongoDB, lack support for transactions.

Our technical contributions can be summarized as follows:

- We introduce VLS, a new technique that enables consistent analytics in disk-resident NoSQL systems (e.g., MongoDB) while, at the same time, attaining low latency and high throughput for updates (Sections II and III). The overheads are kept low through the use of data structures that are compact and support fast operations to manage the snapshots. In addition, storage usage is minimized by sharing data across multiple queries and snapshots.
- We describe a proof-of-concept implementation of the VLS in MongoDB that modifies the native database operations to support the VLS algorithm (Section III-C).
- We report the results of a detailed experimental evaluation, which shows that VLS supports consistent results with low memory usage and computational overheads for analytics and updates (Section IV).

II. Background and Motivation

An important goal of our work is to provide efficient support for concurrent updates and analytics running in a NoSQL system, so as to have results that are both fresh and consistent. Our solution to this problem was inspired by techniques used in CGC. Although these techniques were designed for a different problem, issues arise during a table scan in the presence of updates that are similar to those that arise in CGC. When attempting to reclaim memory, the garbage collector scans the memory and must see a consistent version to avoid premature reclamation. Concurrently, one or more threads of an application may modify that same memory, e.g., by manipulating object pointers. Analogously, a table scan that is performed while multiple updates are concurrently applied should see a consistent snapshot of the table.

Snapshot-at-the-beginning algorithms are a class of CGC algorithms that reclaim only objects that are unreachable at the beginning of a garbage collection scan. The graph of reachable objects is fixed at the moment garbage collection starts, and the collector only sees that *snapshot*, ignoring objects that become unreachable as it runs to ensure termination. In what follows, we describe one such algorithm, Yuasa's algorithm [5], that allows applications to keep running and to make modifications to object pointers while the garbage collection is being executed. We begin by showing, through an example, how the algorithm can be adapted to support a single scan without blocking concurrent updates. Then, we discuss additional challenges that arise in the database context, notably how to support index scans and multiple concurrent analytics, and give an overview of how VLS addresses them.

Single Snapshot: Example. Consider a simple scenario of an air traffic control, which represents a typical ODM Insights use case: there is an airport closure due to a storm and flights must be rerouted. To identify the closest flights, a query is issued to the database that holds information about all flights for a given destination. This database is updated continuously, receiving events as planes move. Each record in the table has a unique id, the flight number, and the current distance to destination airport. Finding the closest flights requires a scan S over the table. For the time being, we assume that there are no indices and S needs to read the entire table.

Figure 2a shows the state, or *snapshot*, of the table at the time S starts. Using transient versioning terminology, we call this snapshot the *stable version* of the table for the analytics, with the corresponding records being the stable versions as well. As in Yuasa's algorithm, where the garbage collector sees the memory state at the time it begins its execution, a query sees the database state as of the time it starts and must not see subsequent changes.

As changes are applied, the snapshot is maintained using two data structures: (i) a bit that is assigned to each record in the base table to indicate whether it is stable (bit set to 0), or whether it has been changed or read by the scan (bit set to 1); and (ii) a *remset* (which stands for *remembered set*) that *remembers* the stable version for the records that have been changed but have yet to be read since the scan started. Similarly, in CGC, the bits indicate which object pointers the garbage collector should read and which pointers it should

skip, while the *remset* stores the overwritten values for the object pointers skipped by the collector.

At the beginning of scan S, all bits are set to `0`, and the *remset* is empty, as shown on Figure 2a. As S proceeds, it reads records and switches the bit from `0` (unread) to `1` (read). During the scan, updates may be applied to the table. Figure 2b shows S having read the first two records and three updates being applied to records that have yet to be read (ahead of S). Update U modifies the value for record 2. Since the current version of this record is the stable one, U first copies this version to the *remset*, flips its state to `1`, indicating that this record has changed, and applies the update. Update D deletes record 4 from the base table, but before doing so, copies its current version to the *remset*. Finally, update I inserts a new record and sets the bit to `1` indicating that it does not belong to the stable version of the table, i.e., it must be skipped by S.

Figure 2c shows three additional updates on records that have their bit set to `1`. The first update is on record 1, which has already been read by S, while the second and third updates are on records 2 and 7, ahead of S but with their bits already set to `1`. These updates can be applied directly, requiring no bit operations or changes to the *remset*. As S proceeds, it skips records 2 and 7, since they have been changed/inserted after S started. Figure 2d shows, in the base table, read records in a gray background, and the skipped ones with a white background. After scanning the base table, S retrieves the stable version of records that have been skipped from the *remset*: record 2, which was modified, and record 4, which was deleted. The combination of the records read from the base table (gray records) and the *remset* records corresponds exactly to the stable version of the table and is what we call a ***virtual lightweight snapshot*** (`VLS`). The snapshot is *virtual* because it is simulated rather than materialized, and it is *lightweight* as the bits and the *remset* are the only additional pieces of information used to maintain the snapshot.

Note that this snapshot ensures consistent results: at the beginning of the scan (Figure 2a), the closest flight is the one in record 1, and since the stable version of the table is maintained, the result reflects that version. If cursor stability were used instead, individual records would be locked as they are read by the scan: after the scan fetches records 0 and 1, and after the updates in record 2 are applied in Figure 2b and Figure 2c, the scan would identify that record 2 contains the closest flight, which is incorrect. In addition, this result reflects neither the stable version of the table, nor the version of the table at the end of the scan: for both versions, the closest flight is still the one in record 1.

Challenges in the Database Context. While we can draw analogies between CGC and consistent evaluation of database queries, there are additional issues that need to be addressed in the database context. One challenge is that garbage collection works for a single scan, while databases need to support concurrent analytics corresponding to distinct, possibly overlapping, snapshots. A naïve approach would be to simply allocate one bit and one *remset* per scan. However, the overlap between concurrent scans can be large, leading to many duplicated record versions across *remsets* and inefficient storage use. To avoid duplicates, we extend the bit logic described above to allow multiple, overlapping snapshots to share a single *remset*, reducing the amount of additional storage required.

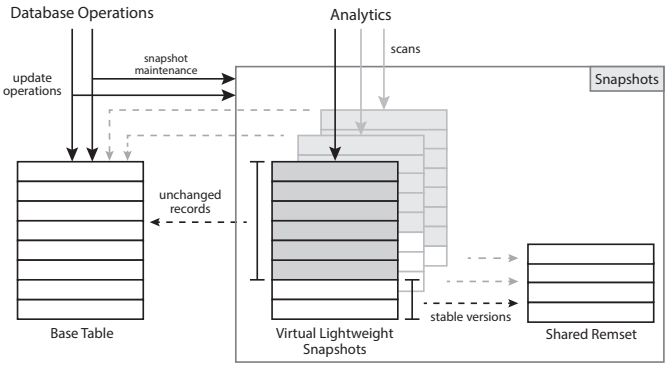


Fig. 3: Overview of the virtual lightweight snapshots approach.

Our experimental results show that sharing *remsets* leads to storage savings of up to 60 times (Section IV).

Another challenge is that garbage collection always performs a full scan, while we need to support *index scans*, i.e., partial scans on the base table. For example, assume that the table from Figure 2 has a B-Tree index on the distance field and a query asks for flights that are at most 400 miles from the airport. When using the index, some records are skipped (e.g., flights with distance greater than 400 miles: records 3, 4, and 6). Updates to these records would still add them to the *remset* as the bit indicates that they are stable, leading to incorrect results: the delete operation in Figure 2b would maintain that version of record 4 in the *remset*, while this version should not be read by the index scan. The `VLS` algorithm ensures that these *spurious records*, i.e., records incorrectly added to the *remset*, are not retrieved by the index scans.

A third challenge is to ensure the integrity of the bits used for records as the system runs, in a way that minimizes the overheads and allows resources to be efficiently reused. As a simple example, consider again Figure 2: at the beginning of the scan, all records have their bit set to `0`, and at the end of the scan, all records have their bit set to `1`. A classic CGC implementation would do a pass to flip the bits to `0` again before a new scan starts. This is obviously expensive in a database context, in particular for large datasets with many millions (or billions) of records. We avoid the need to reset the bits by changing their semantics between two consecutive scans, i.e., in every other execution, `1` becomes the indicator for stable records. As a consequence, these bits can be reused without the need for an expensive operation to reset them. Index scans, on the other hand, require additional bookkeeping: since some records are not read, their bits remain unflipped. Thus, the algorithm needs to ensure that all the bits are properly set for a new scan. While for full scans the overheads for maintaining the bits are amortized, since all records are read, a naïve solution for index scans can result in unacceptable costs, which we avoid in our approach.

III. The VLS Algorithm

Figure 3 shows a high-level overview of the `VLS` architecture. The approach implements versioning at the record level: a virtual lightweight snapshot is created for each read-only query (i.e., analytics) and consists of (a subset of the) records from the base table and from the shared *remset*. A query runs over its snapshot and thus sees a consistent view of the data. Update operations applied to the base table maintain these snapshots

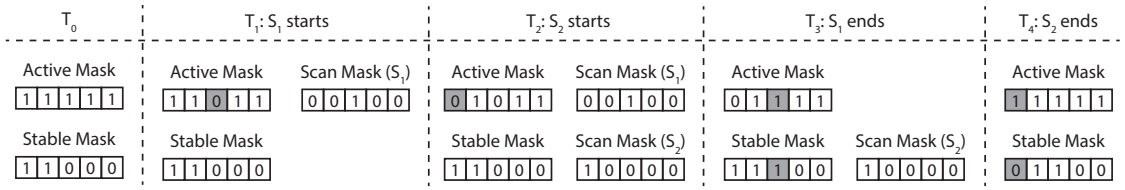


Fig. 4: Global masks in the VLS algorithm.

by copying stable versions of modified records to the *remset*, where these versions can be shared across queries, limiting space overhead.

Our goal is to support consistent analytics without negatively impacting the concurrency in NoSQL systems (e.g., MongoDB) so as to bring consistency to ODM Insights. These systems often lack transactional capabilities, and although some stores have native support for database versioning, this is not an acceptable option for ODM Insights due to their large storage requirements. Thus, we make the following assumptions about the underlying store: (i) there is no support for ACID transactions, and as a consequence, updates are atomic and modify single records; (ii) there is no database versioning; (iii) the data is disk-resident and non-distributed; and (iv) analytics fundamentally rely on a few key data access operations, namely *scans*, which can be either *full scans* over a given base table or *index scans*. Although VLS does not support distributed stores, we are in the process of extending the solution to address such cases.

In the remainder of this section, we describe the VLS algorithm in detail, showing how we address the aforementioned challenges, notably: (i) efficient support for multiple scans, and (ii) efficient support for index access. We also discuss our current VLS implementation at the end of the section.

A. Support for Multiple Scans

The VLS algorithm extends the bit representation and the *remset* used in the single-scan approach from Section II. Instead of relying on a single bit, N-bit vectors are used to handle N concurrent analytics, so that each scan can set these bits independently. Bit vectors are also attached to the *remset* to indicate which record versions correspond to which active scans. Additional bookkeeping is required to: (i) allocate bits to incoming scans, (ii) maintain the meaning of bits (*stable* and changed/read), and (iii) remove records from the shared *remset* when they are no longer needed.

1) Data Structures: Our approach uses several masks that are represented as bit vectors. The algorithm and the choice of specific masks are such that we can always use efficient bitmap operations (Table I), making the solution practical and limiting the overhead added to the database operations (see Section IV). We note that bit vectors have been used before to efficiently deal with a variety of database problems, including concurrent query processing in data-centric engines [10] and multi-query optimization in data warehouses [11].

We first discuss the masks used for scans that are not tied to a specific record.

- **Active Mask**. When a scan starts, it is assigned a specific bit that is identified by its position. A scan uses this bit consistently, i.e., the *same* position, in all masks for its entire duration. To assign a position to an arriving scan, we need to know which positions are available. This is done by using the global N-bit vector *active mask*: if position i in *active mask* has bit 1, then position i is not being used by any active scan; otherwise, if the bit is 0, position i has already been assigned.
  While *active mask* is global to the database and is used to control the assignments of scans to bits, the base table maintains a local copy of this mask to inform table updates if stable versions of the records must be maintained in the *remset* (i.e., if there are active scans while updates are in progress). This copy is stored in the N-bit vector *local active mask*. We show later, while describing the database operations, how these masks are synchronized.
- **Stable Mask**. The global N-bit vector *stable mask* stores which value in each bit means *stable*. For instance, if position i in *stable mask* is 0, then 0 corresponds to stable for that position. Initially, *stable* is represented by 0 in all positions, i.e., the *stable mask* is initialized as a vector of bits set to 0.
- **Scan Mask**. In addition to *active mask*, which globally keeps track of which bits have been allocated, each scan needs to know which bit it owns. Therefore, each scan keeps a mask indicating which position it uses, represented by the N-bit vector *scan mask*. In this mask, the position with bit value 1 is the one assigned to the scan—all the other positions are set to 0.

Figure 4 illustrates the use of these masks. Their values change only when a scan starts or completes. At time T_0, no scan is active and *active mask* only contains bits with value 1. Because two scans were executed to completion before T_0, *stable mask* indicates that 1 means *stable* for the the first two bits (which were assigned to these two scans), and that 0 means *stable* for the last three bits. When scan S_1 starts at time T_1, it is given an available bit (here, the third bit), reflected in *active mask* by setting the third bit to 0, and a *scan mask* indicating that it should use the third bit for all its operations. Similarly, when scan S_2 starts at time T_2, it is allocated the first bit, and given a corresponding *scan mask*. Once S_1 completes at time T_3, its *scan mask* is released, the third bit in *active mask* reverts to 1, and the meaning of stable is switched from 0 to 1 in *stable mask*. The same occurs when scan S_2 completes at time T_4. At this point, all the bits in *active mask* have value 1, i.e., there are no scans running.

We now present the bit vectors tied to specific records. As described in the previous section, the *remset* is used to store the stable versions of the records that have been modified but that have yet to be read by a scan; note that one record may have different versions in the *remset*, since scans can start at different times. As snapshots for different active scans may overlap, to make efficient use of memory, we use a shared *remset*, along with additional bit masks that indicate which record versions a scan should fetch from it. The following masks are used in either the base table or the *remset*:

TABLE I: Efficient bitmap operations in the VLS algorithm.

Name	Bitmap Operations for Scans and Updates
REMSET_MASK_INS	(*stable mask* **XOR** *status mask*) **OR** *local active mask*
REMSET_MASK_UPD	*scan mask* **OR** *remset status mask*
LCL_ACTIVE_MASK_UPD	*local active mask* **OR** *scan mask*
ACTIVE_MASK_UPD	*active mask* **OR** *scan mask*
STATUS_MASK_UPD	**NOT** (*stable mask* **XOR** *local active mask*)
STATUS_MASK_SCAN_UPD	*status mask* **XOR** *scan mask*
SCAN_TABLE_READ	(*stable mask* **XOR** *status mask*) **AND** *scan mask*
STABLE_FLIP	*stable mask* **XOR** *scan mask*
SCAN_REMSET_READ	*scan mask* **AND** *remset status mask*
IDX_STATUS_MASK_INS	**NOT** (*index active mask*)
IDX_STATUS_MASK_UPD	*index status mask* **OR** *index active mask*
IDX_ACTIVE_MASK_UPD	*index active mask* **OR** *scan mask*
SCAN_IDX_MASK_I_UPD	*index status mask* **AND** (**NOT** (*scan mask*))
SCAN_IDX_MASK_U_UPD	*index status mask* **OR** *scan mask*
IDX_SCAN_READ	*index status mask* **AND** *scan mask*

- **Status Mask**. Each record in the base table is associated with an N-bit vector *status mask*, where each bit corresponds to a different active scan.
- **Remset Status Mask**. The algorithm maintains a mask for each record version in the *remset*: the N-bit vector *remset status mask*. If position i in the *remset status mask* of a record version is `0`, then the active scan S assigned to position i should read this version, i.e., this version belongs to the snapshot for S; otherwise, if the bit value is `1`, S should skip it.

In addition to keeping track of which snapshot a record belongs to, the *remset status mask* is also used to support *memory reclamation* of versions in the *remset* that will no longer be used: if all the bits in a *remset status mask* are `1`, no other scan will read the corresponding version, so the scan can remove this version from the *remset*. This reclamation is *immediate*: a record version is removed *as soon as* it is no longer needed.

Next, we look at how these bit masks are maintained by individual operations on the store: *table updates* and *full scans*. Since our focus is on NoSQL stores, we assume that table updates are atomic, and that there is no transaction manager. While describing the algorithm, we refer to the bitmap operations from Table I. We show an example after presenting the steps of the algorithm.

2) Update Operations: We call U an update operation that inserts, deletes, or modifies a single record.

U modifies a record. First, U uses the bit operation REMSET_MASK_INS and stores its value in a temporary N-bit vector *temp mask*. If all bits in *temp mask* have value `1`, it means that (i) this record has already been modified before (if so, stable versions were already placed in the *remset*), or (ii) all active scans have already accessed it (if so, these scans no longer need this record), or (iii) there are no active scans, or (iv) a combination of the previous; therefore, U simply modifies the record and no operations need to be applied to the masks. Otherwise, if there is at least one bit `0` in *temp mask*, the current version of the record is the stable one for at least one active scan; in this case, this version needs to be maintained in the *remset* prior to the update, and the following actions are executed in order: (1) the current version of the record is added to the *remset*, together with *temp mask*, which corresponds to the *remset status mask* of this version; (2) *status mask* is updated to the result of bit operation STATUS_MASK_UPD, to inform active scans to skip the record; and (3) the record is modified by U.

Note that, in the bitmap operation REMSET_MASK_INS, the expression *stable mask* **XOR** *status mask* checks if, for each bit position in *status mask*, the record is stable (outputting `0` for stable), while the remainder of the operation ensures that only bits having active scans are taken into account. Other operations perform similar **XOR** operations against the *stable mask* to capture the proper stable semantics, including STATUS_MASK_UPD.

U inserts a record. U inserts the new record with a *status mask* generated with the bit operation STATUS_MASK_UPD: this operation guarantees that active scans will skip the record, and that new scans include that record in their snapshots.

U deletes a record. The steps are the same as when modifying a record, except that U deletes the record from the base table, and there is no need to maintain the *status mask* of the record.

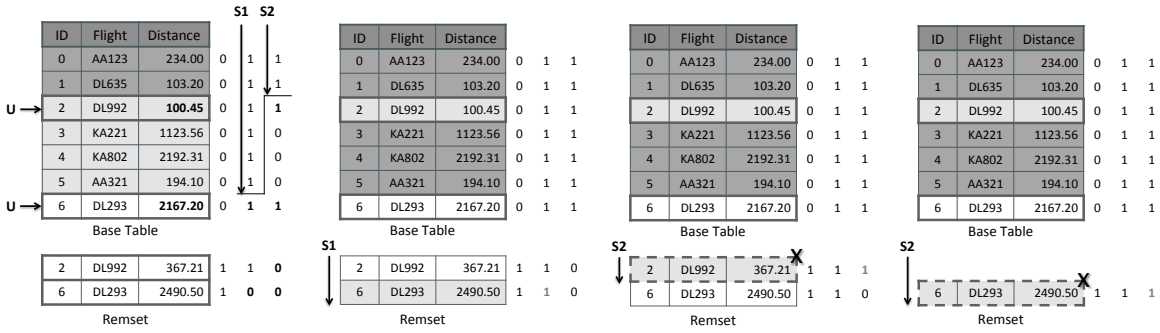
3) Full Scan Operations: We now describe the algorithm for a full scan S.

S begins. If all bits in *active mask* are `0`, there is no position available for S and the scan is placed on a queue for future execution (see discussion at the end of this subsection). Otherwise, a free position i is assigned to S, and both *active mask* and *local active mask* are updated together to have the bit at position i set to `0`. Finally, S generates its *scan mask*, and can start scanning the table.

S reads a record in the table. S stores the value of the bit operation SCAN_TABLE_READ in a temporary N-bit vector called *temp mask*. If all bits in *temp mask* have value `0`, the current version of the record is the stable one for S. S then fetches the record and updates its *status mask* to the value of bit operation STATUS_MASK_SCAN_UPD: this operation updates (i.e., flips) the bit value in position i to reflect that S has already read this record, i.e., that S will not need it anymore. Otherwise, if position i of *temp mask* has value `1`, the current version of this record is not the stable one for S, i.e., this record has already been updated (inserted / modified) after S started, so S skips this record. It is worth noting that, in SCAN_TABLE_READ, the use of *scan mask* ensures that only position i of S is taken into account, and the remainder of the bit operation takes care of capturing the stable semantics, as explained earlier.

S finishes scanning the table. S updates *stable mask* using the bit operation STABLE_FLIP, which ensures that the bit at position i is flipped to change the meaning of *stable*. Besides, bit operation LCL_ACTIVE_MASK_UPD is used by S to update *local active mask*. After scanning the table, S needs to scan the *remset* to get the stable version of records it had skipped before (see the next operation).

S reads a record version in remset. S stores the value of operation SCAN_REMSET_READ in a temporary N-bit vector *temp mask*. If the bit at position i in *temp mask* is `1`, that record does not belong to the snapshot for S and is skipped. Otherwise, S accesses the record and updates *remset status mask* using the REMSET_MASK_UPD bit operation, which flips the bit at position i in *remset status mask* to record the fact that S has already fetched this version, i.e., that S will no longer use the record. At this point, an important part of the algorithm takes place, which is the ***memory reclamation*** of the *remset*: if all bits in the updated *remset status mask* have value `1`, this version will no longer be used by any scan, and S *removes* it from the *remset*. This reclamation is ***immediate***: as soon as a record version becomes unnecessary, it is removed from the *remset*.



(a) (b) (c) (d)

Fig. 5: Some stages and operations of the algorithm: (a) full scans S1 and S2 are reading records 5 and 1, respectively, when two updates modify records 2 and 6 in the base table, saving record 2 for S2, and record 6 for S1 and S2; (b) when S1 scans the *remset*, it skips record 2, and reads record 6; when S2 scans the *remset*, it reads both records 2 (c) and 6 (d), automatically doing memory reclamation.

S ends. S uses ACTIVE_MASK_UPD to update *active mask*, making position i available again for future scans, and synchronizing its value for bit i with *local active mask*.

4) 3-Scan Example: Figure 5 shows some of the stages of VLS using the same example presented in Section II. We assume that two analytic queries (S1 and S2) to find the closest flights from a given airport are executing concurrently, and both perform a full scan over the base table. To simplify the example, we assume that N is 3.

Suppose that *active mask* is 100, *stable mask* is 000, and bits 2 and 1 were assigned to S1 and S2, respectively (bit 1 being the rightmost bit in the masks). Figure 5a shows the state when S1 is reading record 5 and S2 is reading record 1, at which point U modifies record 2. In this case, the current version of record 2 must be stored in the *remset* for S2. Note that S1 has already read this record. Before applying the update, U copies the version to the *remset*, together with *remset status mask* equals to 110, indicating that this version belongs to the snapshot for S2. If another U modifies record 6, the current version needs to be stored for both scans, since it belongs to both snapshots. The record version is copied only once to the *remset*, and *remset status mask* is set to 100, indicating that both scans need to read this version, i.e., the version is shared between the snapshots.

After scanning the table, S1 scans the *remset* (Figure 5b). S1 only fetches record 6, and changes its *remset status mask* accordingly. When S2 starts scanning the *remset*, it reads the versions of records 2 and 6. At that point, both masks are set to 111, which means that no other scan will use them in the future, and S2 can remove these record versions from the *remset* (Figures 5c and 5d).

5) Final Considerations: It it worth mentioning that, conceptually, the VLS algorithm can be used to run any number of concurrent analytics, but in practice, our approach allocates bit vectors in the database with a given size N, and this value determines the maximum number of concurrent scans. The main reason for this design is that having fixed-size masks avoids the costs of dynamically allocating bit vectors as scans arrive and finish. Also, the algorithm is more efficient when bit operations are implemented using native machine instructions, i.e., N should be set according to the register width of the CPU for optimal performance, as we show in Section IV.

From a query planning point of view, if a new scan request arrives and there are no positions available, i.e., N scans are already active, the scan can be added to a scheduling queue for later execution. When an active scan completes, it signals to this queue so that the next awaiting scan can execute. Instead of waiting for a position on a per-scan basis, it is also possible to allow several queries to share an underlying snapshot. This requires some deeper integration with the query planner, which must decide which requests should share a scan to make best use of computational resources, as well as synchronize execution for the queries sharing a given scan. We plan to address this in future work.

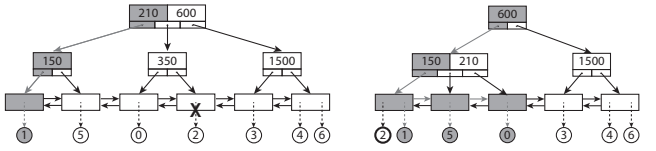
B. Index Support

For the purpose of this discussion, we assume a simple B-Tree index, or a balanced search tree where non-leaf nodes contain a set of keys[2]. A leaf node keeps a set of pointers to records in the base table—the *record pointers*—based on its parent's keys, and this set is also ordered by key. Figure 6a shows an example of a B-Tree index with rank 2 on the distance field of the base table from Figure 2a: record pointers are represented by dashed arrows, and record ids are enclosed in circles.

Index scans are handled in a way similar to full scans, but two additional issues must be taken into account. First, when using the index, only a subset of the index and corresponding base table are scanned, which means that updates operating over records not supposed to be read by the scan may place spurious records in the *remset*. Thus, we also need to ensure the consistency of the bit masks after the index scan finishes. Recall that bits are flipped as the index scan progresses, but records not read by it remain untouched, which may impact the correctness of an upcoming scan using the same bit position.

Second, the physical structure in the index, notably the order of record pointers, may change as updates occur, requiring additional bookkeeping. As an example, consider the B-Tree presented in Figure 6a, and assume a query is issued to retrieve flights that are at most 400 miles away from the airport. Such an index scan, based on the stable version of Figure 2a, must read records 0, 1, 2, and 5. Gray areas and arrows in Figure 6a show the progress of the scan: it starts at the root node and

[2]The approach can be extended to other index types.



(a) Before update on record 2 (b) After update on record 2

Fig. 6: Index scan for flights that are at most 400 miles away. Gray areas and arrows on the B-Tree show the progress of the scan.

traverses down to the first record pointer, linking to record 1. If update U of Figure 2b is applied at this moment, and since the distance value in record 2 changes from 367.21 miles to 100.45 miles, the pointer to record 2 is removed from the index and inserted *before* record 1's pointer (see Figure 6b). Since the scan follows the order in the B-Tree, it will read records 5 and 0 afterwards, thus missing record 2.

To address these issues and correctly support index scans, we make the following adjustments to the `VLS` algorithm:

- To avoid retrieving records added to the *remset* but which should not be read by the index scan (i.e., *spurious records*), we assign a set called *record set* to each index scan. This set contains the ids of records that a scan should read from the *remset*: ids referenced by record pointers read by the index scan while traversing the B-Tree are added to the *record set*, and when retrieving records from *remset*, the scan only reads the stable version of records referenced in *record set*. Since spurious records are not read by the index scan, their ids will not be added to the *record set*, and will thus not be read from the *remset*.
- To ensure that all bits are flipped when the scan finishes, the algorithm needs to do a pass over the *status mask* of the records before allowing a new upcoming scan to use the same bit position. A naïve approach would be for the index scan itself to flip its corresponding bits in these masks before completing and updating *active mask*; however, as mentioned before, scanning all the masks at the end of a scan can be very expensive for large tables, thus degrading the latency and throughput of the system. Instead, we use a *separate thread* to flip the bits in the *status mask* of each record that has not been touched by the index scan; this thread operates in the background *after* the index scan finishes and as other scans read the base table. For this reason, upcoming index scans will only be able to use the same bit position after this background thread finishes. This proved to be significantly more efficient: our solution, when compared to the naïve approach, showed a reduction of over 50% in the update latency in the presence of 64 concurrent analytics.
- To handle updates to the physical structure of the index, we assign one bit mask per record pointer in the B-Tree and maintain these as record pointers are inserted and deleted from the index. The idea of these masks is to inform active scans if a record pointer belongs to the stable snapshot of the scan or not. Additionally, we *postpone* the removal of record pointers from the B-Tree so that active index scans do not miss them; this avoids issues similar to the one mentioned in Figure 6.

1) Data Structures: To maintain stable versions of the index, our approach uses two additional masks:

- **Index Active Mask.** While *active mask* contains information regarding both full and index scans, the global N-bit vector *index active mask* only takes into account index scans. This mask is used exclusively for index scan operations.
- **Index Status Mask.** Each record pointer in a B-Tree has its own N-bit vector *index status mask*. As with the status mask, each bit in the *index status mask* corresponds to an active scan. A position i is `1` if the index scan S_I at position i should skip the record pointer (e.g., the pointer has been either inserted after S_I started, or removed before S_I started); otherwise, if position i is `0`, the corresponding record belongs to the stable version for S_I (e.g., either the pointer has not been altered, or it has been removed after S_I started).
  To capture which record pointers have had their removal postponed, each record pointer also maintains one extra bit that we call *index status bit*: this bit is `1` if the pointer has been flagged for removal, and `0` otherwise. The information provided by *index status bit* is important to reclaim index entries, as well as to inform active index scans about the removal: if the bit is `1`, the scan adds the record id to its *record set* and does not need to follow the record pointer to the table. Note that the removal of a record pointer is triggered by either a record update that changes the position of its pointer in the index, or a record deletion; in both cases, the stable version of the record for the scan is in the *remset*, and we add its id to *record set* so that the scan does not identify it as a spurious record.

It is important to note that if the update is a deletion, although the removal of the record's corresponding pointers is postponed, the deletion of the record itself from the base table is *not* deferred. Therefore, every operation over the B-Tree (besides index scans) must check the *index status bit* to avoid following pointers that may have become invalid. Note also that the database can reclaim index entries every time an index scan finishes, thus avoiding keeping removed record pointers in the B-Tree for long periods of time. We describe this reclamation process later in this section.

2) Index Update Operations: We consider two kinds of updates U_I to record pointers in a B-Tree index: *insertion* and *deletion*. The maintenance of the index does not change, except that, when reallocating record pointers, their masks and bits need to be reallocated as well.

U_I inserts a record pointer in a B-Tree. When a new record pointer is inserted into a leaf node, U_I needs to ensure that active index scans will skip it. U_I inserts the record pointer in the B-Tree with an *index status mask* set to the value of the bit operation IDX_STATUS_MASK_INS. In addition, it is assigned an *index status bit* of value `0`.

U_I deletes a record pointer in a B-Tree. If there are no active index scans, i.e., if *index active mask* is a mask of bits set to `1`, U_I simply deletes the record pointer and no further steps are necessary. Otherwise, if there is at least one active index scan, U_I does not delete the record pointer: the removal is *postponed*. The pointer is still maintained in the leaf node, and U_I updates its *index status mask* to the result of bit operation IDX_STATUS_MASK_UPD: this update ensures that active index scans can still see the record pointer, while new upcoming scans will skip it. In addition, *index status bit* is set to `1` to indicate that the removal of the record pointer has been deferred.

3) Index Scan Operations: For an index scan S_I, the algorithm needs to (i) verify the *index status mask* of record pointers before reading records from the base table; (ii) make use of the *record set* when scanning both the index and the *remset* to deal with spurious records, and (iii) inform the database when to flip the bits in the *status mask* vectors and reclaim index entries.

S_I begins. The steps are the same as for a full scan, but S_I also (i) initializes an empty *record set* before it starts scanning the index and the table, and (ii) updates *index active mask* by setting the position i assigned to S_I to `0`.

S_I reads a record pointer in a B-Tree. Before reading and following the record pointer, S_I uses bit operation IDX_SCAN_READ and stores its value in a temporary N-bit vector *temp mask*. If *temp mask* has one bit set to `1`, it means that the record pointer was either inserted after S_I started, or flagged for removal before S_I started: S_I simply skips the pointer, since it does not belong to its snapshot. Otherwise, if *temp mask* is a vector of bits set to `0`, the record pointer belongs to the snapshot for S_I, and S_I adds the corresponding record id to *record set*; in addition, it checks the value of *index status bit*: if the bit is `1`, the record pointer has been flagged for removal, so S_I skips the pointer (the stable version for the record is in the *remset*); however, if the bit is `0`, S_I follows the pointer to read the record in the table (next operation).

S_I reads a record in the table. The steps are the same as for full scans. Remember that S_I still needs to execute the `VLS` algorithm when reading records in the base table to update the *status mask* of the records and to deal with updates that do not change the physical structure of the index.

S_I finishes scanning the table. The steps are the same as for a full scan, except that the bit mask *index active mask* is also updated with the value of bit operation IDX_ACTIVE_MASK_UPD: this mask is updated before scanning the *remset* so that no upcoming updates in a B-Tree erroneously keep stable version information for S_I.

S_I reads a record version in remset. The steps are the same as for a full scan, except that *record set* is also used. In the algorithm for a full scan, if the bit at position i in *temp mask* is `0`, this record belongs to the snapshot for the scan. For index scans, the record could also be a spurious record. Given that the bit is `0`, we need to: (1) verify if the id of the record is in *record set*: if this is the case, S_I reads this record; otherwise, it skips it; and (2) update *remset status mask* and, if all its bits are `1`, do the memory reclamation. Note that (2) is always executed when the bit value is `0`.

S_I ends. S_I discards its *record set* and starts a background thread that is handled by the database itself and that executes the following operations in order: (1) reclamation of index entries that were modified while S_I was executing; and (2) flipping of the bits in position i for the *status masks* of records neither touched by S_I nor updated. After starting this thread, S_I completes its execution. Note that *active mask* is *not* updated at this point, since we need to make sure all the masks are consistent before allowing new upcoming scans to use the same bit position.

4) Operations for Finalizing an Index Scan: The following are operations started by an index scan S_I right before its completion; they are executed in a background thread and handled by the database.

Index reclamation. The reclamation process iterates over the record pointers of the B-Tree index structure. For each pointer, if the *index status bit* is `0`, the corresponding pointer may have been inserted while S_I was running; in this case, the algorithm updates the *index status mask* to the result of bit operation SCAN_IDX_MASK_I_UPD, so that new upcoming scans using the same bit position do not skip this pointer. Otherwise, if the value of *index status bit* is `1`, the pointer is flagged for removal; first, *index status mask* is updated to the value of bit operation SCAN_IDX_MASK_U_UPD, to indicate that S_I does not need this pointer anymore; then, its updated value is verified: if all its bits are set to `1`, no other index scan will use this pointer, so it can be removed from the index, and its *index status mask* and *index status bit* are discarded.

Resetting the status masks. We iterate over all *status masks* in the table, flipping the bit position used by S_I as if the record is being read by S_I: bit operations SCAN_TABLE_READ and STATUS_MASK_SCAN_UPD are used for the update process, similar to when a scan reads a record in the table. This guarantees that, even if the record was not read by S_I (i.e., even if it does not satisfy its query predicate), its bit is properly flipped to not affect the results of a new scan that will use the same bit position. After this process, *active mask* is updated to the value of bit operation ACTIVE_MASK_UPD, freeing the bit position to new arriving scans.

C. Implementation

We implemented the `VLS` algorithm inside MongoDB, since one of the goals is to support this system as the main data store in the ODM Insights middleware. MongoDB is a document-oriented database that uses Binary JSON (BSON) as a storage format, and it stores collections of key-value pairs. The system, as many other NoSQL stores, neither supports versioning nor guarantees consistency for analytics in the presence of concurrent updates.

Our prototype, `MongoDB-VLS`, extends the built-in database operations from MongoDB with `VLS` capabilities. We modify the standard *create* (i.e., *insert*), *update*, and *delete* operations based on the algorithm from Section III. `MongoDB-VLS` also modifies the built-in scan operations: both full and index scans read and write bit masks, skip records from the base table if necessary, and read the *remset* at the end of the execution. For index scans, as described in the previous section, a background thread is used to ensure that the bit masks are properly set. Our prototype can run MongoDB workloads composed of updates along with aggregate queries[3], which use the built-in scan operations internally.

Masks and *remsets* are stored in memory by the system. For the bit masks, we maintain a mapping between the record locations on disk (composed of a disk file identification and an offset value) and their corresponding masks. Note that operations on *remsets* as well as on bit masks, either global or associated with a record, must be atomic and thread-safe to avoid inconsistencies if two or more operations occur on the same record simultaneously. We rely on the concurrent data structures and atomic operations from Intel's Threading Building Blocks (TBB) library[4] that proved to be the most

[3]http://docs.mongodb.org/manual/aggregation

[4]https://www.threadingbuildingblocks.org/

efficient in our experiments: we use a concurrent hash-map for the *remset*, while bit masks are represented as bit vectors using TBB's atomic interface.

IV. Experimental Evaluation

To assess the effectiveness of VLS when integrated into a NoSQL store and to better understand the costs associated with supporting consistent analytics in the presence of updates, in our experimental evaluation, we compare the performance of MongoDB-VLS against a standalone MongoDB installation. We study the impact of the algorithm on update throughput and latency, as well as on analytics completion time. We also examine the costs incurred when maintaining the data structures required by the snapshots, including memory consumption, and evaluate how the size of the bit vectors impacts our approach.

A. Experimental Setup

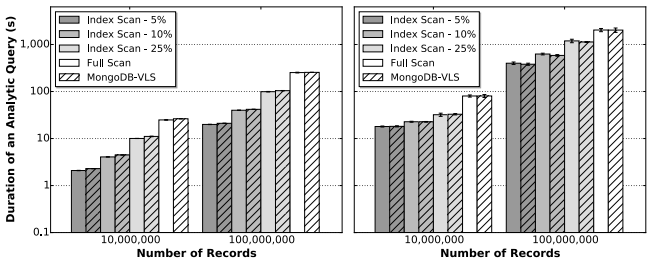
Experiments were run on a server running CentOS (4 16-core 2.3 GHz AMD Opteron 6276 CPUs, 256 GB of RAM, and 4 3TB-SATA drives), using MongoDB 2.5.5 and TBB 4.2 Update 3. We set N to 64, which corresponds to the instruction width of our server, unless otherwise noted.

We ran two different workloads: one for analytics using an aggregate query that counts the total number of records being read, and one for updates. These workloads were generated and run with YCSB [12], a popular open-source benchmark for NoSQL stores. We extended YCSB 0.1.4 to include aggregate queries (using both full and index scans), and ran the benchmark using MongoDB's API. The aggregate query for index scans is the same as for full scans, but includes a condition on the indexed attribute, matching records with key greater or equal to a given input value.

For all experiments, the YCSB client ran on the same machine as the database server. Workloads were run using 10 threads for updates, and one thread per analytics. We evaluated the approach for different *index rates*, indicating how much of the table is being scanned: 5%, 10%, or 25% of the base table. The default attempted update rate was set to 10,000 operations per second (op/s), and keys chosen for the update operations were generated using a zipfian distribution originally provided by YCSB. Each experiment—except the one that verifies the size of the shared *remset*—was executed 10 times, and both the mean and standard deviation (error) were computed. All experiments started with a flushed cache, and we used different YCSB configurations to vary the table size (10 million and 100 million records) and the number of concurrent analytics. For all table sizes, each record used 240 bytes.

B. Experimental Results

Query Execution Time. To understand the overhead associated with the VLS algorithm, we measured the raw analytics performance with no concurrent updates for both MongoDB-VLS and MongoDB. Figure 7a shows, in *log scale*, the query duration for the two table sizes. For a query that performs a full scan, the relative overhead added by the VLS approach is about 5% and 1% for 10 million and 100 million records, respectively; in absolute numbers, MongoDB-VLS increases the scan duration from 24.87s to 26.33s (about 1.46s) for the smaller table, and from 252.85s to 255.37s (about



(a) Without Updates (b) With Updates

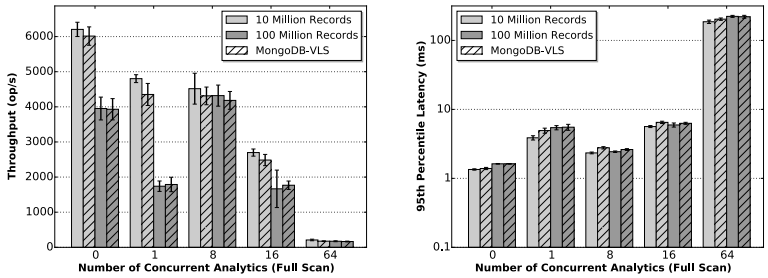
Fig. 7: Duration, in log scale, of an analytic query.

2.52s) for the larger table. For a query that uses an index scan, the overhead is under 10% for both tables. Consider, for example, the index scan that reads 5% of the 10 million-record table: the overhead added by VLS is 9.67% (from 2.09s to 2.29s); for the 100 million-record table, it is 5.67% (from 19.95s to 21.08s). As expected, the relative overheads for index scans are bigger than those for full scans since these require additional bookkeeping; however, when considering the total running times, the increase is negligible: in many cases, less than 1s. We also studied how VLS impacts analytics execution time in the presence of concurrent updates: not surprisingly, the duration of a query increases substantially in both systems, but VLS has a negligible impact for both full and index scans (Figure 7b). Overall, the experiments on query execution time indicate that the overheads incurred by VLS are acceptable, while providing consistent and correct results for analytics.

Update Throughput. Figure 8a shows, for the different table sizes, how the update throughput changes when the number of concurrent analytics using full scans increases. As a baseline, we include the update throughput when no analytics are running (i.e., number of analytics equals to 0); note that VLS has little or no impact over the raw update throughput. When running concurrent analytics, the average overhead added by MongoDB-VLS varies from 2.84% to 16.36% for different table sizes and number of concurrent analytic queries. Nonetheless, most of the error bars overlap, showing that the difference between the average throughput for the two systems is statistically small. For concurrent analytics using index scans, most of the overheads are also small. As Figure 9 shows, the overhead on update throughput for all index rates varies from 0.70% to 16.28%, again with many overlapping error bars. We also experimented with other update rates (e.g., 20,000 op/s, 30,000 op/s, and 100,000 op/s), and obtained similar and consistent results.

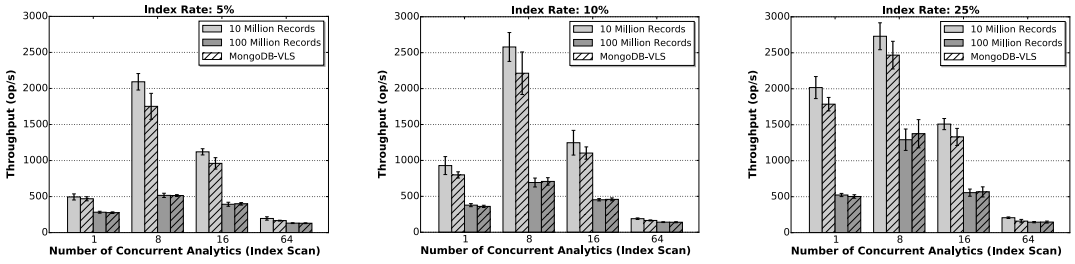
Figures 8a and 9 show interesting trends. First, as expected, as the number of running queries increases, the higher concurrency in the system results in longer updates and smaller throughput. One counter-intuitive feature is that the overall update throughput for both systems is higher for 8 concurrent queries than for a single query. We believe that this is due to the aggressive caching strategy used by MongoDB: with 8 concurrent scans, more records are read and put in memory, making updates faster. This is consistent with the latency results in Figures 8b and 10: updates in the presence of 8 concurrent queries are faster than in the presence of a single query.

Another interesting behavior is that the performance in both MongoDB and MongoDB-VLS for 64 concurrent queries is



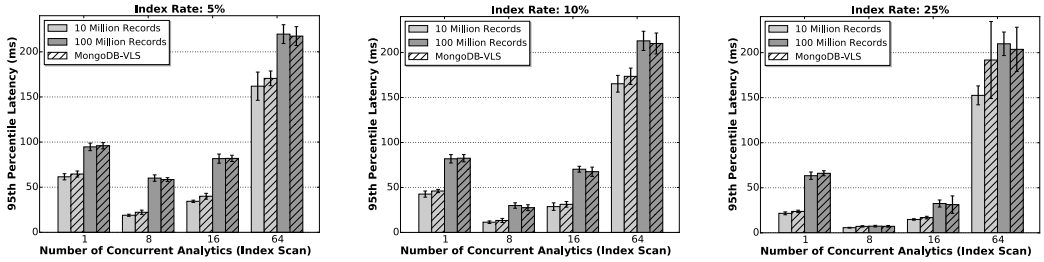
(a) Update Throughput (b) 95th Percentile Update Latency

Fig. 8: Results for (a) update throughput and (b) 95th percentile update latency when running a varying number of concurrent analytics—using full scans—in the presence of updates. Update latency results are in log scale.



(a) (b) (c)

Fig. 9: Update throughput for concurrent analytics—using index scans—for index rates: (a) 5%, (b) 10%, and (c) 25%.



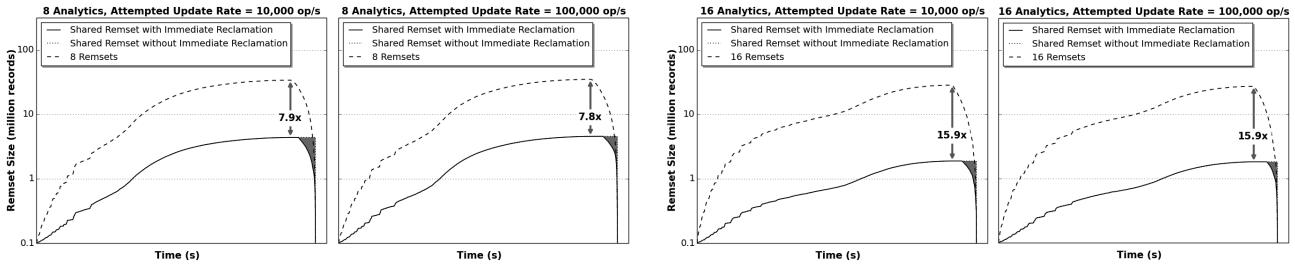
(a) (b) (c)

Fig. 10: 95th percentile update latency for concurrent analytics—using index scans—for index rates: (a) 5%, (b) 10%, and (c) 25%.

significantly lower when compared to the other configurations. This happens mainly due to the higher concurrency in the database and the increase in resource consumption: for 64 concurrent queries, there are 74 threads at total (1 per query, and 10 for updates), which is larger than the number of cores in our server (64), making experiments more sensitive to resource contention. Last, Figures 9 and 10 (the latter shows the latency results discussed later) unveil that higher index rates result in better performance (i.e., higher update throughput and faster updates) in both systems. The main reason for such behavior is the locking mechanism implemented by MongoDB, which yields locks more often for update operations when reading larger regions of the table; therefore, more updates are received and applied while the analytics are running. As the number of concurrent analytics increases, this is almost unnoticeable due to the higher concurrency in the database.

Update Latency. We measured the overhead that `MongoDB-VLS` adds to the duration of an update. We report these results in 95th percentiles, i.e., the maximum latency among 95% of the update operations. Figure 8b presents, in *log scale*, the experimental results for different table sizes and numbers of concurrent analytics using full scans. The overhead is most significant when using `MongoDB-VLS` in the 10 million-record table with a single analytic query, where the percentile increases 27.23%, and with 8 concurrent queries, where there is an increase of 18.64%. However, note that the percentile latency is in a very fine time granularity: in absolute numbers, the latency increases from 3.87ms to 4.93ms for a single analytics, and from 2.34ms to 2.77ms for 8 queries, which can be acceptable for a number of application scenarios. For all other configurations, the overhead varies between 1.62% and 15.04% with overlapping error bars for most of the results, which makes the overhead not statistically significant. Similar results are obtained for concurrent analytics using index scans (Figure 10): most of the overheads are under 18% and not statistically significant. A higher overhead can be noticed for the smaller table when running 8 and 64 concurrent analytics that scan 25% of the table (Figure 10c). Nevertheless, besides the overlapping error bars, the latency increases are small in absolute numbers: from 5.70ms to 7.17ms for 8 analytics, and from 152.57ms to 191.81ms for 64 analytics. For other attempted update rates with which we experimented, ranging from 20,000 op/s to 100,000 op/s, the overheads are also negligible, increasing the update latency in at most tens of milliseconds.

Remset Sharing and Memory Reclamation. To minimize the additional storage required to support the virtual snapshots, the



(a) (b) (c) (d)

Fig. 11: Remset size, in log scale of number of records, for different configurations of number of concurrent queries and attempted update rate in the 100 million-record table. The shaded region shows the additional time that memory is held when early reclamation is not used.

VLS algorithm shares a single *remset* among multiple concurrent analytics and performs immediate memory reclamation when possible. In practice, these features lead to substantial savings. We measured in the 100 million-record table, for different number of concurrent queries (8, 16, and 64) and attempted update rates (10,000 and 100,000 op/s), (i) the size of the shared *remset*, (ii) the total size of *individual* remsets (one *remset* per scan), and (iii) the size of a shared *remset without* immediate reclamation, i.e., records are only removed from the *remset* after the analytics finish. The results are summarized in Figure 11, which shows how the *remset* size (in *log scale* of number of records) varies over time.

The maximum size of the shared *remset* in the presence of 8 concurrent queries with an attempted update rate of 10,000 op/s (Figure 11a) is around 4.3 million records (1.04 GB). In contrast, when using 8 individual *remsets*, the number of records reaches almost 34 million (8.20 GB), i.e., 7.9 times bigger than the shared *remset*. As expected, for a larger update rate (Figure 11b), the queue size increases, but the effectiveness of our solution is similar: the shared *remset* reaches 4.5 million records (1.08 GB), while, for 8 individual *remsets*, the size is 35 million records (8.44 GB). When running more concurrent queries, the savings are even greater: the number of records when using 16 individual *remsets* is about 15.9 times bigger compared to the shared *remset* (Figure 11c and 11d); for 64 analytics, the shared *remset* reduces the size by a factor of about 60 (results not depicted due to lack of space). Note that the *remset* size for 16 concurrent analytics is smaller than for 8 queries, which is an expected result: the higher the number of analytics, the higher the concurrency, and as a consequence, less updates are applied to the database. Figure 11 also shows additional savings (the shaded section) attained by the early reclamation of unused records compared to a reclamation that only takes place after a scan finishes.

Varying the Size of Bit Vectors. Since the VLS algorithm relies on bit operations and bit vectors, it is important to understand how the size of such vectors (N) impacts the performance. We compared, for the 100-million record table, the results on query execution time, throughput, and latency for two values of N: 64 bits (value used in the aforementioned experiments) and 128 bits; our server's registers are 64 bits wide; due to lack of space, we do not present plots for the comparison. When using 128-bit vectors, the duration of an analytics without concurrent updates increases by 9% compared to the performance for 64-bit vectors, while it increases by 6% in the presence of concurrent updates. Overall, the overheads on update throughput when using 128-bit vectors increases by at most 9% for different number of concurrent analytics when compared to the 64-bit results; with respect to update latency, the overhead is bigger—at most 30%—but in absolute numbers, the latency increases by no more than 1.20ms. These results show that, as expected, setting N to the same number as the CPU's register and instruction width (in our case, 64) provides the best results, since native machine instructions can be used more efficiently. Note that, although the overheads are higher for 128-bit vectors, they are still negligible: most of these results, in particular for update throughput and latency, have overlapping error bars when compared to MongoDB. It is worth mentioning that there are servers with up to 512-bit registers[5], thus enabling the maintenance of up to 512 snapshots concurrently; to run a number of concurrent analytics larger than N, an approach that allows snapshots to be shared by multiple queries could be used, as discussed in Section III-A.

V. Related Work

The impact of long-running queries on updates has long been acknowledged as an important issue. Replication can be used to segregate workloads, with long-running queries executing on a replica. This reduces the impact on updates at the cost of higher space requirements and analytics computed on stale information. In regard to this issue, Krishnan et al. [13] propose an alternative model to get approximate (but fresh) results for analytics from stale views using techniques akin to data cleaning. DBMSs can also trade consistency for performance using *cursor stability* [3], which avoids blocking updates by locking one row at a time during scans. Our approach can be thought of as a way to provide consistent results with performance approaching that of cursor stability.

Snapshot semantics can be implemented with MVCC (Multi-Version Concurrency Control) either by storing multiple versions of the database or by dynamically reconstructing an earlier snapshot of the data using the database log [14], [15]. In contrast, our approach focuses on enabling snapshot semantics for analytics without the need of full-fledged versioning, which is a requirement in ODM Insights to limit storage usage. VLS shares similarities with transient versioning techniques [7]–[9], [16], [17], since they rely on versions created specifically to support consistency for OLAP queries. However, these approaches often assume the presence of a transaction manager, making it hard to adapt to current NoSQL stores. In addition, some of these techniques [16] are designed

[5]Modern Intel CPUs have a width of up to 256 bits, and CPUs that have the AVX-512 extension support 512-bit operations.

in the context of main-memory databases, while others [8], [17] have significant initialization and communication costs, and implement versioning at the page—instead of record—level, which potentially creates unnecessary duplicates and space management problems. VLS can be seen as a *snapshot isolation* technique [6], [18] that is lightweight and amenable for implementation in NoSQL systems, since it does not require any transaction manager; differently than Padhye and Tripathi [18], our goal is to neither bring the entire transaction semantics to NoSQL stores, nor rely on native database versioning.

There has been renewed interest in systems that support both OLAP and OLTP workloads. HyPer [19] is an in-memory database that supports snapshots for OLAP-style queries through the *fork* system call. SAP HANA [20] propagates records through different stages, including a write-optimized storage format (for OLTP) and a read-optimized storage format (for OLAP). Hekaton [21] is a memory-optimized OLTP engine for SQL Server that uses an MVCC approach to isolate read-only transactions from updates. HYRISE [22] is a main-memory store that focuses on providing different physical designs for different workloads, but it does not handle aspects related to consistency for hybrid workloads. Note that these systems are specific to in-memory stores, which have fundamentally different requirements from disk-resident storage [23]. Last, R-Store [24] relies on database versioning to support real-time OLAP with OLTP in the same system; it extends HBase as their versioned storage backend, and uses HStreaming to maintain a real-time data cube.

VI. Conclusion and Future Work

As a step towards closing the gap between big and fast data, we proposed *virtual lightweight snapshots* (VLS), a technique that supports consistent analytics without blocking concurrent updates. VLS enables analytics and updates to run in the same system, leading to fresh results that are also correct and consistent. VLS does not require native support for transactions or database versioning, and thus, it can be combined with a number of NoSQL systems. We integrated VLS with MongoDB and performed a detailed experimental evaluation that showed that the overheads incurred by VLS are low and have little impact on query evaluation time, update throughput, and latency. These results suggest that VLS can bring consistency to analytics—while producing correct results—at a low cost, being a practical and efficient solution to support OLTP and OLAP in the ODM Insights middleware.

As future steps, we have plans to include MongoDB-VLS in ODM Insights so as to provide consistency in a future release of the middleware. Although many current use scenarios are non-distributed, we are extending our approach to provide support for distributed data: each node would have their own *remset* and copies for the global masks, and these copies would have to be synchronized whenever a scan begins and ends. However, the synchronization costs and the impact on the index structure are still being investigated. Finally, we are considering additional improvements to the underlying data structures (e.g., using compression to further reduce memory usage) and to the algorithm design (e.g., adapting concepts behind parallel garbage collection to parallelize the approach, and allowing several queries to share a single snapshot).

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