An Innovative Approach to Achieve Compositionality Efficiently using Multi-Version Object Based Transactional Systems *

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Abstract. The rise of multi-core systems has necessitated the need for concurrent programming. However, developing correct, efficient concurrent programs is notoriously difficult. Software Transactional Memory Systems (STMs) are a convenient programming interface for a programmer to access shared memory without worrying about concurrency issues. Another advantage of STMs is that they facilitate compositionality of concurrent programs with great ease. Different concurrent operations that need to be composed to form a single atomic unit is achieved by encapsulating them in a single transaction.

Most of the STMs proposed in the literature are based on read/write primitive operations on memory buffers. We denote them as Read-Write STMs or RWSTMs. On the other hand, there have been some STMs that have been proposed (transactional boosting and its variants) that work on higher level operations such as hash-table insert, delete, lookup, etc. We call them Object STMs or OSTMs.

It was observed in databases that storing multiple versions in RWSTMs provides greater concurrency. In this paper, we combine both these ideas for harnessing greater concurrency in STMs - multiple versions with objects semantics. We propose the notion of Multi-version Object STMs or MVOSTMs. Specifically, we introduce and implement MVOSTM for the hash-table object, denoted as HT-MVOSTM and list object, list-MVOSTM. These objects export insert, delete, and lookup methods within the transactional framework. We also show that both these MVOSTMs satisfy opacity and ensure that transaction with lookup only methods do not abort if unbounded versions are used.

Experimental results show that list-MVOSTM outperform almost two to twenty fold speedup than existing state-of-the-art list based STMs (Trans-list, Boosting-list, NOrec-list, list-MVTO, and list-OSTM). Similarly, HT-MVOSTM shows a significant performance gain of almost two to nineteen times over the existing state-of-the-art hash-table based STMs (ESTM, RWSTMs, HT-MVTO, and HT-OSTM).

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1 Introduction

The rise of multi-core systems has necessitated the need for concurrent programming. However, developing correct concurrent programs without compromising on efficiency is a big challenge. Software Transactional Memory Systems (STMs) are a convenient programming interface for a programmer to access shared memory without worrying about concurrency issues. Another advantage of STMs is that they facilitate compositionality of concurrent programs with great ease. Different concurrent operations that need to be composed to form a single atomic unit is achieved by encapsulating them in a single transaction. Next, we discuss different types of STMs considered in the literature and identify the need to develop multi-version object STMs proposed in this paper.

**Read-Write STMs:** Most of the STMs proposed in the literature (such as NOrec [1], ESTM [2]) are based on read/write operations on transaction objects or t-objects. We denote them as Read Write STMs or RWSTMs. These STMs typically export following methods: (1) `t begin`: begins a transaction, (2) `t read` (or `r`): reads from a t-object, (3) `t write` (or `w`): writes to a t-object, (4) `tryC`: validates and tries to commit the transaction by writing values to the shared memory. If validation is successful, then it returns commit. Otherwise, it returns abort.

**Object STMs:** Some STMs have been proposed that work on higher level operations such as hash-table. We call them Object STMs or OSTMs. It has been shown that OSTMs provide greater concurrency. The concept of Boosting by Herlihy et al. [3], the optimistic variant by Hassan et al. [4] and more recently HT-OSTM system by Peri et al. [5] are some examples that demonstrate the performance benefits achieved by OSTMs.

**Benefit of OSTMs over RWSTMs:** We now illustrate the advantage of OSTMs by considering a hash-table based STM system. We assume that the operations of the hash-table are insert (or `ins`), lookup (or `lu`) and delete (or `del`). Each hash-table consists of B buckets with the elements in each bucket arranged in the form of a linked-list. Figure 1(a) represents a hash-table with the first bucket containing keys \( k_2, k_5, k_7 \). Figure 1(b) shows the execution by two transaction \( T_1 \) and \( T_2 \) represented in the form of a tree. \( T_1 \) performs lookup operations on keys \( k_2 \) and \( k_7 \) while \( T_2 \) performs a delete on \( k_5 \). The delete on key \( k_5 \) generates read on the keys \( k_2, k_5 \) and writes the keys \( k_2, k_5 \) assuming
Multi-Version Object STMs or was exploited in some works such as [3], [4], [5]), in this paper we propose and evaluate RWSTM MVOSTM version to read. Our goal is to evaluate the benefit of T that some other transaction had previously inserted v inserts the value v k on a hash-table ht. Figure 2 (a) represents a history H with two concurrent transactions T ins,lu,del using hash-table object having the same operations as discussed above: illustrate the advantage of MVOSTM Potential benefit of MVOSTMs as compared to single-version OSTMs (SV-OSTMs) we now illustrate the advantage of MVOSTMs as compared to single-version OSTMs (SV-OSTMs) using hash-table object having the same operations as discussed above: ins, lu, del. Figure 2(a) represents a history H with two concurrent transactions T1 and T2 operating on a hash-table ht. T1 first tries to perform a lu on key k2. But due to the absence of key k2 in ht, it obtains a value of null. Then T2 invokes ins method on the same key k2 and inserts the value v2 in ht. Then T2 deletes the key k2 from ht and returns v0 implying that some other transaction had previously inserted v0 into k1. The second method of T1 is lu on the key k1. With this execution, any SV-OSTM system has to return abort
for $T_1$’s $lu$ operation to ensure correctness, i.e., opacity. Otherwise, if $T_1$ would have obtained a return value $v_0$ for $k_1$, then the history would not be opaque anymore. This is reflected by a cycle in the corresponding conflict graph between $T_1$ and $T_2$, as shown in Figure 2(c). Thus to ensure opacity, $SV$-$OSTM$ system has to return abort for $T_1$’s lookup on $k_1$.

In an $MVOSTM$ based on hash-table, denoted as $HT$-$MVOSTM$, whenever a transaction inserts or deletes a key $k$, a new version is created. Consider the above example with a $HT$-$MVOSTM$, as shown in Figure 2(b). Even after $T_2$ deletes $k_1$, the previous value of $v_0$ is still retained. Thus, when $T_1$ invokes $lu$ on $k_1$ after the delete on $k_1$ by $T_2$, $HT$-$MVOSTM$ return $v_0$ (as previous value). With this, the resulting history is opaque with equivalent serial history being $T_1T_2$. The corresponding conflict graph is shown in Figure 2(d) does not have a cycle.

Thus, $MVOSTM$ reduces the number of aborts and achieve greater concurrency than $SV$-$OSTMs$ while ensuring the compositionality. We believe that the benefit of $MVOSTM$ over multi-version $RWSTM$ is similar to $SV$-$OSTM$ over single-version $RWSTM$ as explained above.

$MVOSTM$ is a generic concept which can be applied to any data structure. In this paper, we have considered the list and hash-table based $MVOSTMs$, list-$MVOSTM$ and $HT$-$MVOSTM$ respectively. Experimental results of list-$MVOSTM$ outperform almost two to twenty fold speedup than existing state-of-the-art STMs used to implement a list: Trans-list [10], Boosting-list [3], NOrec-list [1] and $SV$-$OSTM$ [5] under high contention. Similarly, $HT$-$MVOSTM$ shows significant performance gain almost two to nineteen times better than existing state-of-the-art STMs used to implement a hash-table: ESTM [2], NOrec [1] and $SV$-$OSTM$ [5]. To the best of our knowledge, this is the first work to explore the idea of using multiple versions in $OSTMs$ to achieve greater concurrency.

$HT$-$MVOSTM$ and list-$MVOSTM$ use an unbounded number of versions for each key. To address this issue, we develop two variants for both hash-table and list data structures (or DS): (1) A garbage collection method in $MVOSTM$ to delete the unwanted versions of a key, denoted as $MVOSTM$-$GC$. Garbage collection gave a performance gain of 15% over $MVOSTM$ without garbage collection in the best case. Thus, the overhead of garbage collection is less than the performance improvement due to improved memory usage. (2) Placing a limit of $K$ on the number versions in $MVOSTM$, resulting in $KOSTM$. This gave a performance gain of 22% over $MVOSTM$ without garbage collection in the best case.

Contributions of the paper:

– We propose a new notion of multi-version objects based STM system, $MVOSTM$. Specifically develop it for list and hash-table objects, list-$MVOSTM$ and $HT$-$MVOSTM$ respectively.
– We show list-$MVOSTM$ and $HT$-$MVOSTM$ satisfy opacity [7], standard correctness-criterion for STMs.
– Our experiments show that both list-$MVOSTM$ and $HT$-$MVOSTM$ provides greater concurrency and reduces the number of aborts as compared to $SV$-$OSTMs$, single-version $RWSTM$s and, multi-version $RWSTM$s. We achieve this by maintaining multiple versions corresponding to each key.
For efficient space utilization in MVOSTM with unbounded versions we develop Garbage Collection for MVOSTM (i.e. MVOSTM-GC) and bounded version MVOSTM (i.e. KOSTM).

2 Building System Model

The basic model we consider is adapted from Peri et al. [5]. We assume that our system consists of a finite set of $P$ processors, accessed by a finite number of $n$ threads that run in a completely asynchronous manner and communicate using shared objects. The threads communicate with each other by invoking higher-level methods on the shared objects and getting corresponding responses. Consequently, we make no assumption about the relative speeds of the threads. We also assume that none of these processors and threads fail or crash abruptly.

Events and Methods: We assume that the threads execute atomic events and the events by different threads are (1) read/write on shared/local memory objects, (2) method invocations (or $inv$) event and responses (or $rsp$) event on higher level shared-memory objects.

Within a transaction, a process can invoke layer-1 methods (or operations) on a hash-table $t$-object. A hash-table($ht$) consists of multiple key-value pairs of the form $(k, v)$. The keys and values are respectively from sets $\mathcal{K}$ and $\mathcal{V}$. The methods that a thread can invoke are: (1) $t beginnings$: begins a transaction and returns a unique id to the invoking thread. (2) $t insert ht k v$: transaction $T_i$ inserts a value $v$ onto key $k$ in $ht$. (3) $t delete ht k v$: transaction $T_i$ deletes the key $k$ from the hash-table $ht$ and returns the current value $v$ for $T_i$. If key $k$ does not exist, it returns null. (4) $t lookup ht k v$: returns the current value $v$ for key $k$ in $ht$ for $T_i$. Similar to $t delete$, if the key $k$ does not exist then $t lookup$ returns null. (5) $tryC i$: which tries to commit all the operations of $T_i$ and (6) $tryA i$: aborts $T_i$. We assume that each method consists of an $inv$ and $rsp$ event.

We denote $t insert$ and $t delete$ as update methods (or $upd$ method) since both of these change the underlying data structure. We denote $t delete$ and $t lookup$ as return-value methods (or $rv$ method) since these operations return values from $ht$. A method may return ok if successful or $\not\in$ (abort) if it sees an inconsistent state of $ht$.

Transactions: Following the notations used in database multi-level transactions [8], we model a transaction as a two-level tree. The layer-0 consist of read/write events and layer-1 of the tree consists of methods invoked by a transaction.

Having informally explained a transaction, we formally define a transaction $T$ as the tuple $\langle evts(T), <_T \rangle$. Here $evts(T)$ are all the read/write events at layer-0 of the transaction. $<_T$ is a total order among all the events of the transaction.

We denote the first and last events of a transaction $T_i$ as $T_i, firstEvt$ and $T_i, lastEvt$. Given any other read/write event $rw$ in $T_i$, we assume that $T_i, firstEvt <_T rw <_T T_i, lastEvt$. All the methods of $T_i$ are denoted as $methods(T_i)$.

Histories: A history is a sequence of events belonging to different transactions. The collection of events is denoted as $evts(H)$. Similar to a transaction, we denote a history $H$ as tuple $\langle evts(H), <_H \rangle$ where all the events are totally ordered by $<_H$. The set of methods that are in $H$ is denoted by $methods(H)$. A method $m$ is $incomplete$ if $inv(m)$ is in $evts(H)$ but not its corresponding response event. Otherwise, $m$ is $complete$ in $H$. 
Coming to transactions in $H$, the set of transactions in $H$ are denoted as $\text{txns}(H)$. The set of committed (resp., aborted) transactions in $H$ is denoted by $\text{committed}(H)$ (resp., $\text{aborted}(H)$). The set of live transactions in $H$ are those which are neither committed nor aborted. On the other hand, the set of terminated transactions are those which have either committed or aborted.

We denote two histories $H_1$, $H_2$ as equivalent if their events are the same, i.e., $\text{evts}(H_1) = \text{evts}(H_2)$. A history $H$ is qualified to be well-formed if: (1) all the methods of a transaction $T_i$ in $H$ are totally ordered, i.e. a transaction invokes a method only after it receives a response of the previous method invoked by it (2) $T_i$ does not invoke any other method after it received an $\mathcal{A}$ response or after tryC(ok) method. We only consider well-formed histories for OSTM.

A method $m_{ij}$ ($j^{th}$ method of a transaction $T_i$) in a history $H$ is said to be isolated or atomic if for any other event $e_{pq}$ ($r^{th}$ event of method $m_{pq}$) belonging to some other method $m_{pq}$ of transaction $T_p$ either $e_{pq}$ occurs before $\text{inv}(m_{ij})$ or after $\text{rsp}(m_{ij})$.

**Sequential Histories:** A history $H$ is said to be sequential (term used in [11][12]) if all the methods in it are complete and isolated. From now onwards, most of our discussion would relate to sequential histories.

Since in sequential histories all the methods are isolated, we treat each method as a whole without referring to its $\text{inv}$ and $\text{rsp}$ events. For a sequential history $H$, we construct the completion of $H$, denoted $\overline{H}$, by inserting $\text{tryA}_i$ (of some transaction) immediately after the last method of every transaction $T_k \in \text{live}(H)$. Since all the methods in a sequential history are complete, this definition only has to take care of completed transactions.

**Real-time Order and Serial Histories:** Given a history $H$, $<_H$ orders all the events in $H$. For two complete methods $m_{ij}, m_{pq}$ in $\text{methods}(H)$, we denote $m_{ij} <_H m_{pq}$ if $\text{rsp}(m_{ij}) <_H \text{inv}(m_{pq})$. Here MR stands for method real-time order. It must be noted that all the methods of the same transaction are ordered. Similarly, for two transactions $T_i, T_p$ in $\text{term}(H)$, we denote $(T_i <_H T_p)$ if $(T_i, \text{lastEvt}<_H T_p, \text{firstEvt})$. Here TR stands for transactional real-time order.

We define a history $H$ as serial [13] or $t$-sequential [12] if all the transactions in $H$ have terminated and can be totally ordered w.r.t $<_R$, i.e. all the transactions execute one after the other without any interleaving. Intuitively, a history $H$ is serial if all its transactions can be isolated. Formally, $(H$ is serial $) \implies (\forall T_i \in \text{txns}(H) : (T_i \in \text{term}(H)) \land (\forall T_i, T_p \in \text{txns}(H) : (T_i <_R T_p) \lor (T_p <_R T_i)))$. Since all the methods within a transaction are ordered, a serial history is also sequential.

To simplify our analysis, we assume that there exists an initial transaction $T_0$ that invokes $\text{t_delete}$ method on all the keys of the hash-table used by any transaction.

**Valid Histories:** A $\text{rv}\_\text{method}$ ($\text{t_delete}$ and $\text{t_lookup}$) $m_{ij}$ on key $k$ is valid if it returns the value updated by any of the previous committed transaction that updated key $k$. A history $H$ is said to valid if all the $\text{rv}\_\text{methods}$ of $H$ are valid.

**Legal Histories:** A $\text{rv}\_\text{method}$ $m_{ij}$ on key $k$ is legal if it returns the value updated the latest committed transaction that updated key $k$. A history $H$ is said to be legal, if all the $\text{rv}\_\text{methods}$ of $H$ are legal.

We define legality of $\text{rv}\_\text{methods}$ on sequential histories which we use to define correctness criterion as opacity [7]. Consider a sequential history $H$ having a $\text{rv}\_\text{method}
vrmi\textsubscript{j}(ht, k, v) (with v \neq null) as \textit{j}\textsuperscript{th} method belonging to transaction \textit{T}\textsubscript{i}. We define this \textit{vrmi} method to be \textit{legal} if:

\textbf{LR1} If the \textit{vrmi} method is not first method of \textit{T}\textsubscript{i} to operate on \langle ht, k \rangle and \textit{m} was the previous method of \textit{T}\textsubscript{i} on \langle ht, k \rangle. Formally, \textit{vrmi} \textit{j} \neq \textit{H}.firstKeyMth((ht, k), \textit{T}\textsubscript{i}) \wedge (\textit{m} (ht, k, v') = \textit{H}.prevKeyMth((ht, k), \textit{T}\textsubscript{i}) (where v' could be null). Then,

(a) If \textit{m}(ht, k, v') is a \textit{t}\textsubscript{insert} method then \textit{v} = v'.
(b) If \textit{m}(ht, k, v') is a \textit{t}\textsubscript{lookup} method then \textit{v} = v'.
(c) If \textit{m}(ht, k, v') is a \textit{t}\textsubscript{delete} method then \textit{v} = null.

In this case, we denote \textit{m} as the last update method of \textit{vrmi}, i.e., \textit{m}(ht, k, v') = \textit{H}.lastUpd\textsubscript{t} (\textit{vrmi})(ht, k, v)).

\textbf{LR2} If \textit{vrmi} is the first method of \textit{T}\textsubscript{i} to operate on \langle ht, k \rangle and \textit{v} is not null. Formally, \textit{vrmi}(ht, k, v) = \textit{H}.firstKeyMth((ht, k), \textit{T}\textsubscript{i}) \wedge (\textit{v} \neq \textit{null}). Then,

(a) There is a \textit{t}\textsubscript{insert} method \textit{t}\textsubscript{insert}(ht, k, v) in methods(\textit{H}) such that \textit{T}\textsubscript{p} committed before \textit{vrmi}. Formally, \langle \exists \textit{t}\textsubscript{insert}(ht, k, v) \in \textit{methods}(\textit{H}) : \textit{tryC} \preceq_{\textit{MR}} \textit{vrmi}\rangle.
(b) There is no other update method \textit{up}(ht, k) of a transaction \textit{T}\textsubscript{p} operating on \langle ht, k \rangle in \textit{methods}(\textit{H}) such that \textit{T}\textsubscript{p} committed after \textit{vrmi} but before \textit{vrmi}\textsubscript{i}. Formally, \langle \exists \textit{up}(ht, k, v') \in \textit{methods}(\textit{H}) : \textit{tryC} \preceq_{\textit{MR}} \textit{vrmi}\rangle.

In this case, we denote \textit{tryC} as the last update method of \textit{vrmi}, i.e., \textit{tryC}(ht, k, v) = \textit{H}.lastUpd\textsubscript{t} (\textit{vrmi})(ht, k, v)).

\textbf{LR3} If \textit{vrmi} is the first method of \textit{T}\textsubscript{i} to operate on \langle ht, k \rangle and \textit{v} is null. Formally, \textit{vrmi}(ht, k, v) = \textit{H}.firstKeyMth((ht, k), \textit{T}\textsubscript{i}) \wedge (\textit{v} = \textit{null}). Then,

(a) There is a \textit{t}\textsubscript{delete} method \textit{t}\textsubscript{delete}(ht, k, v') in \textit{methods}(\textit{H}) such that \textit{T}\textsubscript{p} (which could be \textit{T}\textsubscript{0} as well) committed before \textit{vrmi}. Formally, \langle \exists \textit{t}\textsubscript{delete}(ht, k, v') \in \textit{methods}(\textit{H}) : \textit{tryC} \preceq_{\textit{MR}} \textit{vrmi}\rangle. Here v' could be null.
(b) There is no other update method \textit{up}(ht, k) of a transaction \textit{T}\textsubscript{p} operating on \langle ht, k \rangle in \textit{methods}(\textit{H}) such that \textit{T}\textsubscript{p} committed after \textit{vrmi} but before \textit{vrmi}\textsubscript{i}. Formally, \langle \exists \textit{up}(ht, k, v') \in \textit{methods}(\textit{H}) : \textit{tryC} \preceq_{\textit{MR}} \textit{vrmi}\rangle.

In this case, we denote \textit{tryC} as the last update method of \textit{vrmi}, i.e., \textit{tryC}(ht, k, v) = \textit{H}.lastUpd\textsubscript{t} (\textit{vrmi})(ht, k, v)).

We assume that when a transaction \textit{T}\textsubscript{i} operates on key \textit{k} of a hash-table \textit{ht}, the result of this method is stored in \textit{local logs} of \textit{T}\textsubscript{i}, \textit{txLog}\textsubscript{i} for later methods to reuse. Thus only the first \textit{rv}-method operating on \langle ht, k \rangle of \textit{T}\textsubscript{i} accesses the shared-memory. The other \textit{rv}-methods of \textit{T}\textsubscript{i} operating on \langle ht, k \rangle do not access the shared-memory and they see the effect of the previous method from the \textit{local logs}, \textit{txLog}\textsubscript{i}. This idea is utilized in LR1. With reference to LR2 and LR3, it is possible that \textit{T}\textsubscript{p} could have aborted before \textit{vrmi}\textsubscript{i}. For LR3, since we are assuming that transaction \textit{T}\textsubscript{0} has invoked a \textit{t}\textsubscript{delete} method on all the keys used of the hash-table objects, there exists at least one \textit{t}\textsubscript{delete} method for every \textit{rv}-method on \textit{k} of \textit{ht}. We formally prove legality in Section 6 and then we finally show that history generated by HT-MVOSTM is opaque [7].

Coming to \textit{t}\textsubscript{insert} methods, since a \textit{t}\textsubscript{insert} method always returns \textit{ok} as they overwrite the node if already present therefore they always take effect on the \textit{ht}. Thus, we denote all \textit{t}\textsubscript{insert} methods as legal and only give legality definition for \textit{rv}-method. We denote a sequential history \textit{H} as \textit{legal} or \textit{linearized} if all its \textit{rv} methods are legal.
To prove that a STM system satisfies opacity, it is useful to consider graph characterization of histories. In this section, we describe the graph characterization of Guerraoui and Kapalka [14] modified for sequential histories.

Consider a history \( H \) which consists of multiple version for each t-object. The graph characterization uses the notion of version order. Given \( H \) and a t-object \( k \), we define a version order for \( k \) as any (non-reflexive) total order on all the versions of \( k \) ever created by committed transactions in \( H \). It must be noted that the version order may or may not be the same as the actual order in which the version of \( k \) are generated in \( H \). A version order of \( H \), denoted as \( \ll_H \), is the union of the version orders of all the t-objects in \( H \).

Consider the history \( H3 \) as shown in Figure 3:

\[
\begin{align*}
T_i & \quad l_{u1}(k_x,0) \quad l_{u5}(k_x,0) \quad m_{n5}(k_x,0) \quad C_1 \\
T_i & \quad l_{u2}(k_x,0) \quad l_{u4}(k_x,0) \quad m_{n2}(k_x,0) \quad C_1 \\
T_i & \quad l_{u3}(k_x,0) \quad m_{n3}(k_x,0) \quad m_{n5}(k_x,0) \quad C_1 \\
T_i & \quad l_{u4}(k_x,0) \quad l_{u5}(k_x,0) \quad m_{n2}(k_x,0) \quad C_1 \\
T_i & \quad l_{u5}(k_x,0) \quad C_1
\end{align*}
\]

Fig. 3: History \( H3 \) in time line view

We define the graph characterization based on a given version order. Consider a history \( H \) and a version order \( \ll \). We then define a graph (called opacity graph) on \( H \) using \( \ll \), denoted as \( OPG(H, \ll) = (V, E) \). The vertex set \( V \) consists of a vertex for each transaction \( T_i \) in \( H \). The edges of the graph are of three kinds and are defined as follows:

1. \( rt(\text{real-time}) \) edges: If commit of \( T_i \) happens before beginning of \( T_j \) in \( H \), then there exist a real-time edge from \( v_i \) to \( v_j \). We denote set of such edges as \( rt(H) \).
2. *rvf* (return value-from) edges: If \( T_j \) invokes \( rv \) method on key \( k_1 \) from \( T_i \) which has already been committed in \( H \), then there exist a return value-from edge from \( v_i \) to \( v_j \). If \( T_i \) is having \( upd \) method as insert on the same key \( k_1 \) then \( ins_i(k_{1,i}, v_{11}) <_H c_i <_H rvm_j(k_{1,i}, v_{11}). \) If \( T_i \) is having \( upd \) method as delete on the same key \( k_1 \) then \( del_i(k_{1,i}, null) <_H c_i <_H rvm_j(k_{1,i}, null). \) We denote set of such edges as \( rvf(H) \).

3. *mv* (multi-version) edges: This is based on version order. Consider a triplet with successful methods as \( up_i(k_{1,i}, u), \) \( rvm_j(k_{1,i}, u), \) \( up_k(k_{1,k}, v) \), where \( u \neq v \). As we can observe it from \( rvm_j(k_{1,i}, u), c_i <_H rvm_j(k_{1,i}, u) \) if \( k_{1,i} \ll k_{1,k} \) then there exist a multi-version edge from \( v_j \) to \( v_k \). Otherwise \( (k_{1,k} \ll k_{1,i}) \), there exist a multi-version edge from \( v_k \) to \( v_i \). We denote set of such edges as \( mv(H, \ll) \).

We now show that if a version order \( \ll \) exists for a history \( H \) such that it is acyclic, then \( H \) is opaque.

Using this construction, the \( OPG(H_3, \ll_{H_3}) \) for history \( H_3 \) and \( \ll_{H_3} \) is given above is shown in Figure 4. The edges are annotated. The only mv edge from \( T_4 \) to \( T_3 \) is because of t-objects \( k_y, k_z \). \( T_4 \) lookups value \( v_{12} \) for \( k_z \) from \( T_1 \) whereas \( T_3 \) also inserts \( v_{32} \) to \( k_z \) and commits before \( lu_4(ht, k_z, 1, v_{12}) \).

![Fig. 4: OPG(H3, \ll_{H3})](image-url)

Given a history \( H \) and a version order \( \ll \), consider the graph \( OPG(\overline{H}, \ll) \). While considering the \( rt \) edges in this graph, we only consider the real-time relation of \( H \) and not \( \overline{H} \). It can be seen that \( rt^*_{H} \subseteq rt^*_{\overline{H}} \) but with this assumption, \( rt(H) = rt(\overline{H}). \) Hence, we get the following property.

*Property 1.* The graphs \( OPG(H, \ll) \) and \( OPG(\overline{H}, \ll) \) are the same for any history \( H \) and \( \ll. \)
**Definition 1.** For a t-sequential history $S$, we define a version order $\ll_{S}$ as follows: For two version $k_{x,i}, k_{x,j}$ created by committed transactions $T_{i}, T_{j}$ in $S$, $(k_{x,i} \ll_{S} k_{x,j} \iff T_{i} \ll_{S} T_{j})$.

Now we show the correctness of our graph characterization using the following lemmas and theorem.

**Lemma 1.** Consider a legal t-sequential history $S$. Then the graph $OPG(S, \ll_{S})$ is acyclic.

**Proof.** We numerically order all the transactions in $S$ by their real-time order by using a function $ord$. For two transactions $T_{i}, T_{j}$, we define $ord(T_{i}) < ord(T_{j}) \iff T_{i} \ll_{S} T_{j}$. Let us analyze the edges of $OPG(S, \ll_{S})$ one by one:

- rt edges: It can be seen that all the rt edges go from a lower ord transaction to a higher ord transaction.

- rvf edges: If $T_{j}$ lookups $k_{x}$ from $T_{i}$ in $S$ then $T_{i}$ is a committed transaction with $ord(T_{i}) < ord(T_{j})$. Thus, all the rvf edges go from a lower ord transaction to a higher ord transaction.

- mv edges: Consider a successful rv method $rvm_{j}(k_{x}, u)$ and a committed transaction $T_{k}$ writing $v$ to $k_{x}$ where $u \neq v$. Let $c_{i}$ be $rvm_{j}(k_{x}, u)$’s lastWrite. Thus, $up_{i}(k_{x,i}, u) \in evts(T_{i})$. Thus, we have that $ord(T_{i}) < ord(T_{j})$. Now there are two cases w.r.t $T_{i}$; (1) Suppose $ord(T_{k}) < ord(T_{i})$. We now have that $T_{k} \ll_{S} T_{i}$. In this case, the mv edge is from $T_{i}$ to $T_{k}$. (2) Suppose $ord(T_{k}) < ord(T_{j})$, which implies that $T_{i} \ll_{S} T_{k}$. Since $S$ is legal, we get that $ord(T_{j}) < ord(T_{k})$. This case also implies that there is an edge from $ord(T_{i})$ to $ord(T_{k})$. Hence, in this case as well the mv edges go from a transaction with lower ord to a transaction with higher ord.

Thus, in all the three cases the edges go from a lower ord transaction to higher ord transaction. This implies that the graph is acyclic.

**Lemma 2.** Consider two histories $H$, $H'$ that are equivalent to each other. Consider a version order $\ll_{H}$ on the t-objects created by $H$. The mv edges $mv(H, \ll_{H})$ induced by $\ll_{H}$ are the same in $H$ and $H'$.

**Proof.** Since the histories are equivalent to each other, the version order $\ll_{H}$ is applicable to both of them. It can be seen that the mv edges depend only on events of the history and version order $\ll$. It does not depend on the ordering of the events in $H$. Hence, the mv edges of $H$ and $H'$ are equivalent to each other.

Using these lemmas, we prove the following theorem.

**Theorem 1.** A valid history $H$ is opaque iff there exists a version order $\ll_{H}$ such that $OPG(H, \ll_{H})$ is acyclic.

**Proof.** (if part): Here we have a version order $\ll_{H}$ such that $G_{H} = OPG(H, \ll)$ is acyclic. Now we have to show that $H$ is opaque. Since the $G_{H}$ is acyclic, a topological sort can be obtained on all the vertices of $G_{H}$. Using the topological sort, we can generate a t-sequential history $S$. It can be seen that $S$ is equivalent to $H$. Since $S$ is obtained by
a topological sort on $G_H$ which maintains the real-time edges of $H$, it can be seen that $S$ respects the rt order of $H$, i.e. $\prec_{RT}^H \subseteq \prec_{RT}^S$.

Similarly, since $G_H$ maintains return value-from (rvf) order of $H$, it can be seen that if $T_j$ lookups $k_x$ from $T_i$ in $H$ then $T_i$ terminates before $lu_i(k_x)$ and $T_j$ in $S$. Thus, $S$ is valid. Now it remains to be shown that $S$ is legal. We prove this using contradiction. Assume that $S$ is not legal. Thus, there is a successful rv_method $rm_j(k_x, v)$ such that its lastWrite in $S$ is $T_k$ and $T_k$ updates value $v(\neq u)$ to $k_x$, i.e. $up_k(k_x, v) \in evts(T_k)$. Further, we also have that there is a transaction $T_i$ that insert $u$ to $k_x$, i.e. $up_i(k_x, u) \in evts(T_i)$. Since $S$ is valid, as shown above, we have that $T_i \prec_S^{RT} T_k \prec_S^{RT} T_j$.

Now in $\ll_H$, if $k_x, k \ll_H k_x, i$ then there is an edge from $T_k$ to $T_i$ in $G_H$. Otherwise $(k_x, i \ll_H k_x, k)$, there is an edge from $T_j$ to $T_k$. Thus in either case $T_k$ can not be in between $T_i$ and $T_j$ in $S$ contradicting our assumption. This shows that $S$ is legal.

(Only if part): Here we are given that $H$ is opaque and we have to show that there exists a version order $\ll$ such that $G_H = OPG(H, \ll)(= OPG(H, \ll_R), Property [1]$ is acyclic. Since $H$ is opaque there exists a legal t-sequential history $S$ equivalent to $H$ such that it respects real-time order of $H$. Now, we define a version order for $S$. $\ll_S$ as in Definition [1]. Since the $S$ is equivalent to $H$, $\ll_S$ is applicable to $H$ as well. From Lemma [1] we get that $G_S = OPG(S, \ll_S)$ is acyclic. Now consider $G_H = OPG(H, \ll_S)$. The vertices of $G_H$ are the same as $G_S$. Coming to the edges,

- rt edges: We have that $S$ respects real-time order of $H$, i.e. $\prec_{RT}^H \subseteq \prec_{RT}^S$. Hence, all the rt edges of $H$ are a subset of $S$.
- rvf edges: Since $\ll_H$ and $S$ are equivalent, the return value-from relation of $\ll_H$ and $S$ are the same. Hence, the rvf edges are the same in $G_H$ and $G_S$.
- mv edges: Since the version-order and the operations of the $H$ and $S$ are the same, from Lemma [2] it can be seen that $\ll_H$ and $S$ have the same mv edges as well.

Thus, the graph $G_H$ is a subgraph of $G_S$. Since we already know that $G_S$ is acyclic from Lemma [1] we get that $G_H$ is also acyclic.

4 HT-MVOSTM Design and Data Structure

HT-MVOSTM is a hash-table based MVOSTM that explores the idea of using multiple versions in OSTMs for hash-table object to achieve greater concurrency. The design of HT-MVOSTM is similar to HT-OSTM [5] consisting of $B$ buckets. All the keys of the hash-table in the range $\mathcal{K}$ are statically allocated to one of these buckets.

Each bucket consists of linked-list of nodes along with two sentinel nodes head and tail with values $-\infty$ and $+\infty$ respectively. The structure of each node is as (key, lock, marked, vl, nnext). The key is a unique value from the set of all keys $\mathcal{K}$. All the nodes are stored in increasing order in each bucket as shown in Figure 3(a), similar to any linked-list based concurrent set implementation [6][15]. In the rest of the document, we use the terms key and node interchangeably. To perform any operation on a key, the corresponding lock is acquired. marked is a boolean field which represents whether the key is deleted or not. The deletion is performed in a lazy manner similar to the concurrent linked-lists structure [6]. If the marked field is true then key corresponding to the node has been logically deleted; otherwise, it is present. The vl field of the
node points to the version list (shown in Figure 5(b)) which stores multiple versions corresponding to the key. The last field of the node is \textit{nnext} which stores the address of the next node. It can be seen that the list of keys in a bucket is as an extension of lazy-list [6]. Given a node \textit{n} in the linked-list of bucket \textit{B}, we denote its fields as \textit{n.key(k.key)}, \textit{n.lock(k.lock)}, \textit{n.marked(k.marked)}, \textit{n.vl(k.vl)}, \textit{n.nnext(k.nnext)}.

The structure of each version in the \textit{vl} of a key \textit{k} is \langle \textit{ts}, \textit{val}, \textit{rvl}, \textit{vnext} \rangle as shown in Figure 5(b). The field \textit{ts} denotes the unique timestamp of the version. In our algorithm, every transaction is assigned a unique timestamp when it begins which is also its \textit{id}. Thus \textit{ts} of this version is the timestamp of the transaction that created it. All the versions in the \textit{vl} of \textit{k} are sorted by \textit{ts}. Since the timestamps are unique, we denote a version, \textit{ver} of a node \textit{n} with key \textit{k} having \textit{tsj} as \textit{n.vl[j].ver} or \textit{k.vl[j].ver}. The corresponding fields in the version as \textit{k.vl[j].ts}, \textit{k.vl[j].val}, \textit{k.vl[j].rvl}, \textit{k.vl[j].vnext}.

The field \textit{val} contains the value updated by an update transaction. If this version is created by an insert method \textit{t.insert}(\textit{ht}, \textit{k}, \textit{v}) by transaction \textit{T}_i, then \textit{val} will be \textit{v}. On the other hand, if the method is \textit{t.delete}(\textit{ht}, \textit{k}) with the return value \textit{v}, then \textit{val} will be \textit{null}. In this case, as per the algorithm, the node of key \textit{k} will also be marked. \textit{HT-MVOSTM} algorithm does not immediately physically remove deleted keys from the hash-table. The need for this is explained below. Thus a \textit{rv_method} (\textit{t.delete} or \textit{t.lookup}) on key \textit{k} can return null when it does not find the key or encounters a null value for \textit{k}.

The \textit{rvl} field stands for \textit{return value list} which is a list of all the transactions that executed \textit{rv_method} on this version, i.e., those transactions which returned \textit{val}. The field \textit{vnext} points to the next available version of that key.

Number of versions in \textit{vl} (the length of the list) as per \textit{HT-MVOSTM} can be bounded or unbounded. It can be bounded by having a limit on the number of versions such as \textit{K}. Whenever a new version \textit{ver} is created and is about to be added to \textit{vl}, the length of \textit{vl} is checked. If the length becomes greater than \textit{K}, the version with lowest \textit{ts} (i.e., the oldest) is replaced with the new version \textit{ver} and thus maintaining the length back to \textit{K}. If the length is unbounded, then we need a garbage collection scheme to delete unwanted versions for efficiency.

\textbf{Marked Nodes:} \textit{HT-MVOSTM} stores keys even after they have been deleted (nodes which have \textit{marked} field as true). This is because some other concurrent transactions could read from a different version of this key and not the \textit{null} value inserted by the
deleting transaction. Consider for instance the transaction \( T_1 \) performing \( t\text{lookup}(ht, k) \) as shown in Figure 2(b). Due to the presence of previous version \( v_0 \), \( HT-MVOSTM \) could return this earlier version \( v_0 \) for \( t\text{lookup}(ht, k) \) method. Whereas, it is not possible for \( HT-OSTM \) to return the version \( v_0 \) because \( k \) has been removed from the system after the delete by \( T_2 \). In that case, \( T_1 \) would have to be aborted. Thus as explained in Section 1, storing multiple versions increases the concurrency.

To store deleted keys along with live keys (or unmarked node) in a lazy-list will increase the traversal time to access unmarked nodes. Consider the Figure 6, in which there are four keys \( \langle k_5, k_8, k_9, k_{12} \rangle \) present in the list. Here \( \langle k_5, k_8, k_9 \rangle \) are marked (or deleted) nodes while \( k_{12} \) is unmarked. Now, consider an access the key \( k_{12} \) as by \( HT-MVOSTM \) as a part of one of its methods. Then \( HT-MVOSTM \) would have to unnecessarily traverse the marked nodes to reach key \( k_{12} \).

This motivated us to modify the lazy-list structure of nodes in each bucket to form a skip list based on red and blue links. We denote it as red-blue lazy-list or lazyrb-list. This idea was earlier explored by Peri et al. in developing OSTM. lazyrb-list consists of nodes with two links, red link (or RL) and blue link (or BL). The node which are not marked (or not deleted) are accessible from the head via BL. While all the nodes including the marked ones can be accessed from the head via RL. With this modification, let us consider the above example of accessing unmarked key \( k_{12} \). It can be seen that \( k_{12} \) can be accessed much more quickly through BL as shown in Figure 7. Using the idea of lazyrb-list, we have modified the structure of each node as \( \langle key, lock, marked, vl, RL, BL \rangle \). Further, for a bucket \( B \), we denote its linked-list as \( B.lazyrb-list \).

5 Working of \( HT-MVOSTM \)

As explained in Section 2, \( HT-MVOSTM \) exports \( t\text{begin}, t\text{insert}, t\text{delete}, t\text{lookup}, \text{tryC} \) methods. \( t\text{delete}, t\text{lookup} \) are rv_methods while \( t\text{insert}, t\text{delete} \) are upd_methods. We treat \( t\text{delete} \) as both rv_method as well as upd_method. The rv_methods return the current value of the key. The upd_methods, update to the keys are first noted down in local log, \( txLog \). Then in the \( \text{tryC} \) method after validations of these updates are transferred to the shared memory. We now explain the working of rv_method and upd_method.

\( t\text{begin}() \) : A thread invokes a new transaction \( T_i \) using this method. This method returns a unique id to the invoking thread by incrementing an atomic counter. This unique id is also the timestamp of the transaction \( T_i \). For convenience, we use the notation that \( i \) is the timestamp (or id) of the transaction \( T_i \). The transaction \( T_i \) local log \( txLog_i \) is initialized in this method.
**rv_methods** - `t_delete((ht, k, v))` and `t_lookup((ht, k, v))`: Both these methods return the current value of key `k`. Algorithm [1] gives the high-level overview of these methods. First, the algorithm checks to see if the given key is already in the local log, `txLog` of `T_i` (Line [2]). If the key is already there then the current `rv_i` method is not the first method on `k` and is a subsequent method of `T_i` on `k`. So, we can return the value of `k` from the `txLog_i`.

If the key is not present in the `txLog_i`, then `HT-MVOSTM` searches into shared memory. Specifically, it searches the bucket to which `k` belongs to. Every key in the range `k` is statically allocated to one of the `B` buckets. So, the algorithm searches for `k` in the corresponding bucket, say `B_k` to identify the appropriate location, i.e., identify the correct predecessor or `pred` and current or `curr` keys in the lazyrb-list of `B_k` without acquiring any locks similar to the search in lazy-list [6]. Since each key has two links, `RL` and `BL`, the algorithm identifies four node references: two `pred` and two `curr` according to red and blue links. They are stored in the form of an array with `preds[0]` and `curr[0]` corresponding to blue links; `preds[1]` and `curr[1]` corresponding to red links. If both `preds[1]` and `curr[1]` nodes are unmarked then the `pred`, `curr` nodes of both red and blue links will be the same, i.e., `preds[0] = preds[1]` and `curr[0] = curr[1]`. Thus depending on the marking of `pred`, `curr` nodes, a total of two, three or four different nodes will be identified. Here, the search ensures that `preds[0].key ≤ preds[1].key < k ≤ curr[0].key ≤ curr[1].key`.

Next, the re-entrant locks on all the `pred`, `curr` keys are acquired in increasing order to avoid the deadlock. Then all the `pred` and `curr` keys are validated by `rv.Validation()` in Line [7] as follows: (1) If `pred` and `curr` nodes of blue links are not marked, i.e, `¬preds[0].marked` && `¬curr[1].marked`. (2) If the next links of both blue and red `pred` nodes point to the correct `curr` nodes: `(preds[0],BL = curr[1])` && `(preds[1],RL = curr[0])`.

If any of these checks fail, then the algorithm retries to find the correct `pred` and `curr` keys. It can be seen that the validation check is similar to the validation in concurrent lazy-list [6].

Next, we check if `k` is in `B_k.lazyrb-list`. If `k` is not in `B_k`, then we create a new node for `k` as: `<key = k, lock = false, marked = false, vl = v, vnext = φ>` and insert it into `B_k.lazyrb-list` such that it is accessible only via `RL` since this node is marked (Line [12]). This node will have a single version `v` as: `<ts = 0, val = nil, rl = i, vnext = φ>`. Here invoking transaction `T_i` is creating a version with timestamp `0` to ensure that `rv_methods` of other transactions will never abort. As we have explained in Figure [2](b) of Section [1], even after `T_2` deletes `k_1`, the previous value of `v_0` is still retained. Thus, when `T_i` invokes `lu` on `k_1` after the delete on `k_1` by `T_2`. `HT-MVOSTM` will return `v_0` (as previous value). Hence, each `rv_methods` will find a version to read while maintaining the infinite version corresponding to each key `k`. In `rl`, `T_i` adds the timestamp as `i` in it and `vnext` is initialized to empty value. Since `val` is null and the `n`, this version and the node is not technically inserted into `B_k.lazyrb-list`.

If `k` is in `B_k.lazyrb-list` then, `k` is the same as `curr[0]` or `curr[1]` or both. Let `n` be the node of `k` in `B_k.lazyrb-list`. We then find the version of `n`, `ver_j` which has the timestamp `j` such that `j` has the largest timestamp smaller than `i` (timestamp of `T_i`). Add `i` to `ver_j`’s `rl` (Line [22]). Then release the locks, update the local log `txLog_i` in Line [24] and return the value stored in `ver_j.val` in Line [26].
Algorithm 1 \(rv\) method: Could be either \(t\_delete (ht, k, v)\) or \(t\_lookup (ht, k, v)\) on key \(k\) that maps to bucket \(B_b\).

```
1: procedure rv\_method(ht, k, v)
2:   if (k \in txLog_i) then
3:     Update the local log and return val.
4:   else
5:     Search in lazyrb-list to identify the \(preds[]\) and \(currs[]\) for \(k\) using BL and RL in bucket \(B_b\).
6:     Acquire the locks on \(preds[]\) and \(currs[]\) in increasing order.
7:     if \(\langle rv\_Validation(preds[], currs[])\rangle\) then
8:       Release the locks and goto Line 5.
9:   end if
10:  if \((k \notin B_b, lazyrb-list)\) then
11:     Create a new node \(n\) with key \(k\) as: \(\langle key = k, lock = false, marked = false, vl = v, nnext = \phi\rangle\).
12:     The \(vl\) consists of a single element \(v\) with \(ts\) as \(i^\ast\).
13:     Create the version \(v\) as: \((ts = 0, val = null, rvl = i, snext = \phi)\).
14:     Insert \(n\) into \(B_b, lazyrb-list\) such that it is accessible only via RLs. \(n\) is marked \(\ast\)
15:     Release the locks; update the \(txLog_i\) with \(k\).
16:   return null.
17: end if
18:  Identify the version \(ver_j\) with \(ts = j\) such that \(j\) is the largest timestamp smaller than \(i\).
19:  if \((ver_j = null)\) then
20:    goto Line 11.
21: end if
22:  Add \(i\) into the \(rvl\) of \(ver_j\).
23:  retVal = ver_j \(ravl\).
24:  Release the locks; update the \(txLog_i\) with \(k\) and \(retVal\).
25: end if
26: return retVal.
27: end procedure
```

**upd\_methods - \(t\_insert\) and \(t\_delete\):** Both the methods create a version corresponding to the key \(k\). The actual effect of \(t\_insert\) and \(t\_delete\) in shared memory will take place in \(tryC\). Alg 2 represents the high-level overview of \(tryC\).

Initially, to avoid deadlocks, algorithm sorts all the \(keys\) in increasing order which are present in the local log, \(txLog_i\). In \(tryC\), \(txLog_i\) consists of \(upd\_methods (t\_insert\) or \(t\_delete\)) only. For all the \(upd\_methods (opn_i)\) it searches the key \(k\) in the shared memory corresponding to the bucket \(B_b\). It identifies the appropriate location \(\langle pred\) and \(curr\rangle\) of key \(k\) using BL and RL (Line 33 in the lazyrb-list of \(B_b\) without acquiring any locks similar to \(rv\_method\) explained above.

Next, it acquires the re-entrant locks on all the \(pred\) and \(curr\) keys in increasing order. After that, all the \(pred\) and \(curr\) keys are validated by \(tryC\_Validation\) in Line 33 as follows: (1) It does the \(rv\_Validation()\) as explained above in the \(rv\_method\). (2) If key \(k\) exists in the \(B_b, lazyrb-list\) and let \(n\) as a node of \(k\). Then algorithm identifies the version of \(n, ver_j\) which has the timestamp \(j\) such that \(j\) has the largest timestamp smaller than \(i\) (timestamp of \(T_i\)). If any higher timestamp \(k\) of \(T_i\) than timestamp \(i\) of \(T_i\) exist in \(ver_j, rvl\) then algorithm returns \(Abort\) in Line 36.

If all the above steps are true then each \(upd\_methods\) exist in \(txLog_i\) will take the effect in the shared memory after doing the \(intraTransValidation()\) in Line 41. If two \(upd\_methods\) of the same transaction have at least one common shared node among its recorded \(pred\) and \(curr\) keys, then the previous \(upd\_method\) effect may overwrite if the current \(upd\_method\) of \(pred\) and \(curr\) keys are not updated according to the updates done by the previous \(upd\_method\). Thus to solve this we have \(intraTransValidation()\)
that modifies the *pred* and *curr* keys of current operation based on the previous operation in Line 41.

**Algorithm 2** `tryC(T_i)`: Validate the upd-methods of the transaction and then commit

```
procedure `tryC(T_i)`
1. /*Operation name (opn) which could be either `iInsert` or `iDelete`*/
2. /*Sort the keys of `txLog_i` in increasing order*/
3. for all (opn_i in `txLog_i`) do
4.     if (opn_i == `iInsert`) then
5.         Search in `(lazyrb-list)` to identify the `preds[]` and `currs[]` for k of opn_i, using BL and RL in bucket B_k.
6.         Acquire the locks on `preds[]` and `currs[]` in increasing order.
7.     if `tryCValidation()` then
8.         return `Abort`.
9.     end if
10. end for
11. end for
12. end procedure
```

Next, we check if upd-method is `iInsert` and k is in `B_k.lazyrb-list`. If k is not in `B_k`, then create a new node n for k as: `(key = k, lock = false, marked = false, vl = v, vnext = φ)`. This node will have a single version v as: `(ts = i, val = v, rvl = φ, vnext = φ)`. Here i is the timestamp of the transaction T_i invoking this method; rvl and vnext are initialized to empty values. We set the val as v and insert n into `B_k.lazyrb-list` such that it is accessible via RL as well as BL and set the lock field to true (Line 45). If k is in `B_k.lazyrb-list` then, k is the same as `currs[0]` or `currs[1]` or both. Let n be the node of k in `B_k.lazyrb-list`. Then, we create the version v as: `(ts = i, val = v, rvl = φ, vnext = φ)` and insert the version into `B_k.lazyrb-list` such that it is accessible via RL (Line 47).

Subsequently, we check if upd-method is `iDelete` and k is in `B_k.lazyrb-list`. Let n be the node of k in `B_k.lazyrb-list`. Then create the version v as: `(ts = i, val = null, rvl = φ, vnext = φ)` and insert the version into `B_k.lazyrb-list` such that it is accessible only via RL (Line 49).

Finally, at Line 52 it updates the `pred` and `curr` of opn_i in local log, `txLog_i`. At Line 54 releases the locks on all the `pred` and `curr` in increasing order of keys to avoid deadlocks and return `Commit`.

We illustrate the helping methods of `rv` method and upd_method as follows:
**rv\_Validation\():** It is called by both the rv\_method and upd\_method. It identifies the conflicts among the concurrent methods of different transactions. Consider an example shown in Figure 21 where two concurrent conflicting methods of different transactions are working on the same key \(k_3\). Initially, at stage \(s_1\) in Figure 21(c) both the conflicting method optimistically (without acquiring locks) identify the same \(pred\) and \(curr\) keys for key \(k_3\) from \(B_k.lazyrb\)-list in Figure 21(a). At stage \(s_2\) in Figure 21(c), method \(ins_1(k_3)\) of transaction \(T_1\) acquired the lock on \(pred\) and \(curr\) keys and inserted the node into \(B_k.lazyrb\)-list as shown in Figure 21(b). After successful insertion by \(T_1\), \(pred\) and \(curr\) has been changed for \(lu_2(k_3)\) at stage \(s_3\) in Figure 21(c). So, the above modified information is delivered by rv\_Validation method at Line 57 when \((preds[0].BL \neq curr[1])\) for \(lu_2(k_3)\). After that again it will find the new \(pred\) and \(curr\) for \(lu_2(k_3)\) and eventually it will commit.

![Algorithm 3 rv\_Validation()](attachment:image.png)

![Fig. 8: rv\_Validation](attachment:image.png)

---

**Algorithm 3 rv\_Validation()**

```
56:  procedure RV\_VALIDATION()
57:      if ((preds[0].marked) || (curr[1].marked)) || (preds[0].BL) \neq curr[1]) then
58:         return false.
59:      else
60:         return true.
61:      end if
62:  end procedure
```

![Fig. 9: tryC\_Validation](attachment:image.png)

---

(a) Underlying list at stage \(s_1\)
(b) Successful insertion of \(k_3\) at stage \(s_2\)
(c) Two concurrent conflicting methods

---

(a) Opaque history: \(T_1\) Abort
(b) Underlying Data structure(DS)
**tryC_Validation:** It is called by upd_method in tryC. First it does the rv_Validation() in Line 64. If its successful and key $k$ exists in the $B_k.lazyrb-list$ and let $n$ as a node of $k$. Then algorithm identifies the version of $n$, $ver_j$ which has the timestamp $j$ such that $j$ has the largest timestamp smaller than $i$ (timestamp of $T_i$). If any higher timestamp $T_k$ than timestamp $T_i$ exist in $ver_j.rvl$ then algorithm returns false (in Line 71) and eventually return Abort in Line 36. Consider an example as shown in Figure 9 (a), where second method $ins_1$ of transaction $T_1$ returns Abort because higher timestamp of transaction $T_2$ is already present in the $rvl$ of version $T_0$ identified by $T_1$ in Figure 9 (b).

```plaintext
Algorithm 4 tryC_Validation()

63: procedure TRYC_VALIDATION()
64: if (!rv_Validation()) then
65:   Release the locks and retry.
66: end if
67: if ($k \in B_k.lazyrb-list$) then
68:   Identify the version $ver_j$ with $ts = j$ such that $j$ is the largest timestamp smaller than $i$.
69:   for all $T_k$ in $ver_j.rvl$ do
70:     if (TS($T_k$) > TS($T_i$)) then
71:       return false.
72:     end if
73:   end for
74: end if
75: return true.
76: end procedure
```

**intraTransValidation:** It is called by upd_method in tryC. If two upd_methods of the same transaction have at least one common shared node among its recorded pred and curr keys, then the previous upd_method effect may overwrite if the current upd_method of pred and curr keys are not updated according to the updates done by the previous upd_method. Thus to solve this we have intraTransValidation() that modifies the pred and curr keys of current operation based on the previous operation from Line 78 to Line 87. Consider an example as shown in Figure 10, where two upd_-methods of transaction $T_1$ are $ins_1(k_3)$ and $ins_2(k_5)$ in Figure 10 (c). At stage $s_1$ in Figure 10 (c) both the upd_methods identify the same pred and curr from underlying

```plaintext
Algorithm 5 intraTransValidation()

77: procedure INTRA_TransVALIDATION()
78: if ((preds[0].marked) || (preds[0].BL \# curr[1])) then
79:   if (opn[k] == Insert) then
80:     preds[0].i ← preds[0].k.BL.
81:   else
82:     preds[0].i ← preds[0].k.
83:   end if
84: end if
85: if (preds[1].RL \# curr[0]) then
86:   preds[1].i ← preds[1].k.RL.
87: end if
88: end procedure
```
DS as \(B_k.lazyrb-list\) shown in Figure 10 (a). After the successful insertion done by first \texttt{upd\_method} at stage \(s_2\) in Figure 10 (c), key \(k_3\) is part of \(B_k.lazyrb-list\) (Figure 10 (b)). At stage \(s_3\) in Figure 10 (c), \(\text{ins}_{12}(k_5)\) identified \((\text{preds}[0].BL \neq \text{currs}[1])\) in \textit{intraTransValidation()} at Line 78. So it updates the \(\text{preds}[0]\) in Line 80 for correct updation in \(B_k.lazyrb-list\).

![Fig. 10: Intra transaction validation](image)

### 6 Correctness of HT-MVOSTM

In this section, we will prove that our implementation satisfies opacity. Consider the history \(H\) generated by \textit{MVOSTM} algorithm. Recall that only the \texttt{STM\_begin}, \texttt{rv\_method}, \texttt{upd\_method} (or \texttt{tryC}) access shared memory.

Note that \(H\) is not necessarily sequential: the transactional methods can execute in overlapping manner. To reason about correctness we have to prove \(H\) is opaque. Since we defined opacity for histories which are sequential, we order all the overlapping methods in \(H\) to get an equivalent sequential history. We then show that this resulting sequential history satisfies method.

We order overlapping methods of \(H\) as follows: (1) two overlapping \texttt{STM\_begin} methods based on the order in which they obtain lock over \texttt{counter}; (2) two \texttt{rv\_method} accessing the same key \(k\) by their order of obtaining lock over \(k\); (3) a \texttt{rv\_method} \(\text{rvm}_i(k)\) and a \texttt{tryC}_j of a transaction \(T_j\) which has written to \(k\), are similarly ordered by their order of obtaining lock over \(k\); (4) similarly, two \texttt{tryC} methods based on the order in which they obtain lock over same key \(k\).

Combining the real-time order of events with above mentioned order, we obtain a partial order which we denote as \(\text{lockOrder}_H\). (It is a partial order since it does not order overlapping \texttt{rv\_method} on different \textit{keys} or an overlapping \texttt{rv\_method} and a \texttt{tryC} which do not access any common \textit{key}).

In order for \(H\) to be sequential, all its methods must be ordered. Let \(\alpha\) be a total order or \textit{linearization} of methods of \(H\) such that when this order is applied to \(H\), it is sequential. We denote the resulting history as \(H^\alpha = \text{linearize}(H, \alpha)\). We now argue about the validity of histories generated by the algorithm.

**Lemma 3.** Consider a history \(H\) generated by the algorithm. Let \(\alpha\) be a linearization of \(H\) which respects \(\text{lockOrder}_H\), i.e. \(\text{lockOrder}_H \subseteq \alpha\). Then \(H^\alpha = \text{linearize}(H, \alpha)\) is valid.
Proof. Consider a successful \texttt{rv} method \texttt{rvm}_\texttt{j}(k) that returns value \( v \). The \texttt{rv} method first obtains lock on key \( k \). Thus the value \( v \) returned by the \texttt{rv} method must have already been stored in \( k \)'s version list by a transaction, say \( T_j \) when it successfully returned OK from its \texttt{tryC} method (if \( T_j \neq T_0 \)). For this to have occurred, \( T_j \) must have successfully locked and released \( k \) prior to \( T_j \)'s locking method. Thus from the definition of lockOrder, we get that \texttt{tryC}_\texttt{j}(ok) occurs before \texttt{rvm}_\texttt{j}(k, v) which also holds in \( \alpha \).

If \( T_j \) is \( T_0 \), then by our assumption we have that \( T_j \) committed before the start of any method in \( H \). Hence, this automatically implies that in both cases \( H^\alpha \) is valid.

It can be seen that for proving correctness, any linearization of a history \( H \) is sufficient as long as the linearization respects lockOrder. The following lemma formalizes this intuition,

**Lemma 4.** Consider a history \( H \). Let \( \alpha \) and \( \beta \) be two linearizations of \( H \) such that both of them respect \texttt{lockOrder}_H, i.e. lockOrder \( H^\alpha \subseteq \alpha \) and lockOrder \( H^\beta \subseteq \beta \). Then, \( H^\alpha = \text{linearize}(H, \alpha) \) is opaque if \( H^\beta = \text{linearize}(H, \beta) \) is opaque.

Proof. From Lemma 3 we get that both \( H^\alpha \) and \( H^\beta \) are valid histories. Now let us consider each case

**If:** Assume that \( H^\alpha \) is opaque. Then, we get that there exists a legal t-sequential history \( S \) that is equivalent to \( H^\alpha \). From the definition of \( H^\beta \), we get that \( H^\alpha \) is equivalent to \( H^\beta \). Hence, \( S \) is equivalent to \( H^\beta \) as well. We also have that, \( \lhd_{H^\beta} \subseteq \lhd_S \). From the definition of lockOrder, we get that \( \lhd_{H^\beta} = \lhd_{\text{lockOrder}_H} = \lhd_{\text{linearize}(H, \beta)} \). This automatically implies that \( \lhd_{H^\beta} \subseteq \lhd_S \). Thus \( H^\beta \) is opaque as well.

**Only if:** This proof comes from symmetry since \( H^\alpha \) and \( H^\beta \) are not distinguishable.

This lemma shows that, given a history \( H \), it is enough to consider one sequential history \( H^\alpha \) that respects lockOrder for proving correctness. If this history is opaque, then any other sequential history that respects lockOrder is also opaque.

Consider a history \( H \) generated by HT-MVOSTM algorithm. We then generate a sequential history that respects lockOrder. For simplicity, we denote the resulting sequential history of HT-MVOSTM as \( H_{to} \). Let \( T_i \) be a committed transaction in \( H_{to} \) that writes to \( k \) (i.e. it creates a new version of \( k \)).

To prove the correctness, we now introduce some more notations. We define \( H_{to}.stl(T_i, k) \) as a committed transaction \( T_i \) such that \( T_i \) has the smallest timestamp greater than \( T_i \) in \( H_{to} \) that writes to \( k \) in \( H_{to} \). Similarly, we define \( H_{to}.lts(T_k, k) \) as a committed transaction \( T_k \) such that \( T_k \) has the largest timestamp smaller than \( T_i \) that writes to \( k \) in \( H_{to} \). Using these notations, we describe the following properties and lemmas on \( H_{to} \).

**Property 2.** Every transaction \( T_i \) is assigned an unique numeric timestamp \( i \).

**Property 3.** If a transaction \( T_i \) begins after another transaction \( T_j \) then \( j < i \).

**Property 4.** If a transaction \( T_k \) lookup key \( k_x \) from (a committed transaction) \( T_j \) then \( T_j \) is a committed transaction updating to \( k_x \) with \( j \) being the largest timestamp smaller than \( k \). Formally, \( T_j = H_{to}.lts(k_x, T_k) \).
Lemma 5. Suppose a transaction $T_k$ lookup $k_z$ from (a committed transaction) $T_j$ in $H_{to}$, i.e. $\{up_j(k_z,v), rvm_k(k_z,v)\} \in evts(H_{to})$. Let $T_i$ be a committed transaction that updates to $k_z$, i.e. $up_i(k_z,u) \in evts(T_i)$. Then, the timestamp of $T_i$ is either less than $T_j$’s timestamp or greater than $T_k$’s timestamp, i.e. $i < j \oplus k < i$ (where $\oplus$ is XOR operator).

Proof. We will prove this by contradiction. Assume that $i < j \oplus k < i$ is not true. This implies that, $j < i < k$. But from the implementation of rv_method and tryC methods, we get that either transaction $T_i$ is aborted or $T_k$ lookup $k$ from $T_i$ in $H$. Since neither of them are true, we get that $j < i < k$ is not possible. Hence, $i < j \oplus k < i$.

To show that $H_{to}$ satisfies opacity, we use the graph characterization developed above in Section 3. For the graph characterization, we use the version order defined using timestamps. Consider two committed transactions $T_i, T_j$ such that $i < j$. Suppose both the transactions write to key $k$. Then the versions created are ordered as: $k_i \ll k_j$. We denote this version order on all the keys created as $\ll_{to}$. Now consider the opacity graph of $H_{to}$ with version order as defined by $\ll_{to}$, $G_{to} = OPG(H_{to}, \ll_{to})$. In the following lemmas, we will prove that $G_{to}$ is acyclic.

Lemma 6. All the edges in $G_{to} = OPG(H_{to}, \ll_{to})$ are in timestamp order, i.e. if there is an edge from $T_j$ to $T_i$ then the $j < i$.

Proof. To prove this, let us analyze the edges one by one,

- rt edges: If there is a rt edge from $T_j$ to $T_i$, then $T_j$ terminated before $T_i$ started. Hence, from Property 3 we get that $j < i$.
- rvf edges: This follows directly from Property 4
- mv edges: The mv edges relate a committed transaction $T_k$ updates to a key $k$, $up_k(k,v)$; a successful rv_method $rvm_j(k,u)$ belonging to a transaction $T_j$ lookup $k$ updated by a committed transaction $T_i$, $up_i(k,u)$. Transactions $T_i, T_k$ create new versions $k_i, k_j$ respectively. According to $\ll_{to}$, if $k_k \ll_{to} k_i$, then there is an edge from $T_k$ to $T_i$. From the definition of $\ll_{to}$ this automatically implies that $k < i$. On the other hand, if $k_i \ll_{to} k_k$ then there is an edge from $T_j$ to $T_k$. Thus in this case, we get that $i < k$. Combining this with Lemma 4, we get that $j < k$.

Thus in all the cases we have shown that if there is an edge from $T_j$ to $T_i$ then the $j < i$.

Theorem 2. Any history $H_{to}$ generated by HT-MVOSTM is opaque.

Proof. From the definition of $H_{to}$ and Lemma 3, we get that $H_{to}$ is valid. We show that $G_{to} = OPG(H_{to}, \ll_{to})$ is acyclic. We prove this by contradiction. Assume that $G_{to}$ contains a cycle of the form, $T_{c1} \rightarrow T_{c2} \rightarrow ... \rightarrow T_{cm} \rightarrow T_{c1}$. From Lemma 6, we get that, $c1 < c2 < ... < cm < c1$ which implies that $c1 < c1$. Hence, a contradiction. This implies that $G_{to}$ is acyclic. Thus from Theorem 1 we get that $H_{to}$ is opaque.

Now, it is left to show that our algorithm is live, i.e., under certain conditions, every operation eventually completes. We have to show that the transactions do not deadlock. This is because all the transactions lock all the keys in a predefined order. As discussed earlier, the STM system orders all keys. We denote this order as accessOrder and denote it as $\ll_{ao}$. Thus $k_1 \ll_{ao} k_2 \ll_{ao} ... \ll_{ao} k_n$.

From accessOrder, we get the following property
Property 5. Suppose transaction $T_i$ accesses shared objects $p$ and $q$ in $H$. If $p$ is ordered before $q$ in accessOrder, then $lock(p)$ by transaction $T_i$ occurs before $lock(q)$. Formally, $(p \prec_{ao} q) \Leftrightarrow (lock(p) < _H lock(q))$.

Theorem 3. HT-MVOSTM with unbounded versions ensures that $rv$ methods do not abort.

Proof. This is self explanatory with the help of HT-MVOSTM algorithm because each key is maintaining multiple versions in the case of unbounded versions. So $rv$ method always finds a correct version to read it from. Thus, $rv$ methods do not abort.

Theorem 3 gives us a nice property a transaction with $t_{lookup}$ only methods will not abort.

7 Experimental Evaluation

In this section, we present our experimental results. We have two main goals in this section: (1) evaluating the benefit of multi-version object STMs over the single-version object STMs, and (2) evaluating the benefit of multi-version object STMs over multi-version read-write STMs. We use the HT-MVOSTM described in Section 5 as well as the corresponding list-MVOSTM which implements the list object. We also consider extensions of these multi-version object STMs to reduce the memory usage. Specifically, we consider a variant that implements garbage collection with unbounded versions and another variant where the number of versions never exceeds a given threshold $K$.

Experimental system: The Experimental system is a large-scale 2-socket Intel(R) Xeon(R) CPU E5-2690 v4 @ 2.60GHz with 14 cores per socket and two hyper-threads (HTs) per core, for a total of 56 threads. Each core has a private 32KB L1 cache and 256 KB L2 cache (which is shared among HTs on that core). All cores on a socket share a 35MB L3 cache. The machine has 32GB of RAM and runs Ubuntu 16.04.2 LTS. All code was compiled with the GNU C++ compiler (G++) 5.4.0 with the build target x86_64-Linux-gnu and compilation option -std=c++1x -O3.

STM implementations: We have taken the implementation of NOrec-list [1], Boosting-list [3], Trans-list [10], ESTM [2], and RWSTM directly from the TLDS framework [3]. And the implementation of OSTM and MVTO published by the author. We implemented our algorithms in C++. Each STM algorithm first creates $N$-threads, each thread, in turn, spawns a transaction. Each transaction exports the following methods as follows: $t_{begin}$, $t_{insert}$, $t_{lookup}$, $t_{delete}$ and $tryC$.

Methodology: We have considered two types of workloads: (W1) Li - Lookup intensive (90% lookup, 8% insert and 2% delete) and (W2) Ui - Update intensive(10% lookup, 45% insert and 45% delete). The experiments are conducted by varying number of threads from 2 to 64 in power of 2, with 1000 keys randomly chosen. We assume that the hash-table of HT-MVOSTM has five buckets and each of the bucket (or list in case of list-MVOSTM) can have a maximum size of 1000 keys. Each transaction, in turn,
executes 10 operations which include `t_lookup`, `t_delete` and `t_insert` operations. We take an average over 10 results as the final result for each experiment.

**Results:** Figure 11 shows `HT-MVOSTM` outperforms all the other algorithms (HT-MVTO, RWSTM, ESTM, HT-OSTM) by a factor of 2.6, 3.1, 3.8, 3.5 for workload type $W_1$ and by a factor of 10, 19, 6, 2 for workload type $W_2$ respectively. As shown in Figure 11, List based MVOSTM (list-MVOSTM) performs even better compared with the existing state-of-the-art STMs (list-MVTO, NOrec-list, Boosting-list, Trans-list, list-OSTM) by a factor of 12, 24, 22, 20, 2.2 for workload type $W_1$ and by a factor of 169, 35, 24, 28, 2 for workload type $W_2$ respectively. As shown in Figure 12 for both types of workloads, HT-MVOSTM and list-MVOSTM have the least number of aborts.

![Fig. 11: Performance of HT-MVOSTM and list-MVOSTM](image)

![Fig. 12: Aborts of HT-MVOSTM and list-MVOSTM](image)
MVOSTM-GC and KOSTM: For efficient memory utilization, we develop two variations of MVOSTM. The first, MVOSTM-GC, uses unbounded versions but performs garbage collection. **This is achieved by deleting non-latest versions whose timestamp is less than the timestamp of the least live transaction.** MVOSTM-GC gave a performance gain of 15% over MVOSTM without garbage collection in the best case. The second, KOSTM, keeps at most $K$ versions by deleting the oldest version when $(K + 1)^{th}$ version is created by a current transaction. As KOSTM has limited number of versions while MVOSTM-GC can have infinite versions, the memory consumed by KOSTM is 21% less than MVOSTM. (Implementation details for both are in the below.)

We have integrated these variations in both hash-table based (HT-MVOSTM-GC and HT-KOSTM) and linked-list based MVOSTMs (list-MVOSTM-GC and list-KOSTM), we observed that these two variations increase the performance, concurrency and reduces the number of aborts as compared to MVOSTM.

Experiments show that these variations outperform the corresponding MVOSTMs. Between these two variations, KOSTM perform better than MVOSTM-GC as shown in Figure 11 and Figure 12. HT-KOSTM helps to achieve a performance speedup of 1.22 and 1.15 for workload type W1 and speedup of 1.15 and 1.08 for workload type W2 as compared to HT-MVOSTM and HT-MVOSTM-GC respectively. Whereas list-KOSTM (with four versions) gives a speedup of 1.1, 1.07 for workload type W1 and speedup of 1.25, 1.13 for workload type W2 over the list-MVOSTM and list-MVOSTM-GC respectively.

**Mid-Intensive workload:** Similar to Lookup intensive and Update intensive experiments we have conducted experiments for mid intensive workload (W3) as well where we have considered 50% update operations(25% insert, 25% delete) and 50% read operations. Under this setting again MVOSTM outperforms all the other algorithms for both HT-MVOSTM and list-MVOSTM. Figure 13 shows HT-MVOSTM outperforms all the other algorithms(HM-MVTO, RWSTM, ESTM, HT-OSTM) by a factor of 10.1, 4.85, 3, 1.4 for workload type W3 respectively. As shown in Figure 13 list-based MVOSTM (list-MVOSTM) performs even better compared with the existing state-of-the-art algorithms(list-MVTO, NOrec-list, Boosting-list, Trans-list, list-OSTM) by a factor of 26.8, 29.4, 25.9, 20.9, 1.58 for workload type W3 respectively. Even the abort count for MVOSTM is least as compared to all other algorithms for both HT-MVOSTM as well as list-MVOSTM. Figure 14 shows our experimental results for the abort count.

**Garbage Collection in MVOSTMs (MVOSTM-GC):** Providing multiple versions to increase the performance of OSTMs in MVOSTMs lead to more space requirements. As many unnecessary versions pertain in the memory a technique to remove these versions or to collect these garbage versions is required. Hence we came up with the idea of garbage collection in MVOSTMs. We have implemented garbage collection for MVOSTM for both hash-table and linked-list based approaches. Each transaction, in the beginning, logs its time stamp in a global list named as ALTL (All live transactions list), which keeps track of all the live transactions in the system. Under the optimistic approach of STM, each transaction performs its updates in the shared memory in the update execution phase. Each transaction in this phase performs some validations and if all validations are completed successfully a version of that key is created by that transaction. When
Fig. 13: Performance of HT-MVOSTM and list-MVOSTM

Fig. 14: Aborts of HT-MVOSTM and list-MVOSTM
a transaction goes to create a version of a key in the shared memory, it checks for the least time stamp live transaction present in the ALTL. If the current transaction is the one with least timestamp present in ALTL, then this transaction deletes all the older versions of the current key and create a version of its own. If current transaction is not the least timestamp live transaction then it doesn’t do any garbage collection. In this way, we ensure each transaction performs garbage collection on the keys it is going to create a version on. Once the transaction, changes its state to commit, it removes its entry from the ALTL. As shown in Figure 15 and Figure 16 MVOSTM with garbage collection (HT-MVOSTM-GC and list-MVOSTM-GC) performs better than MVOSTM without garbage collection.

Finite version MVOSTM (KOSTM): Another technique to efficiently use memory is to restrict the number of versions rather than using unbounded number of versions, without compromising on the benefits of multi-version. KOSTM, keeps at most $K$ versions by deleting the oldest version when $(K + 1)^{th}$ version is created by a validated transaction. That is, once a key reaches its maximum number of versions count $K$, no new version is created in a new memory location rather new version overrides the version with the oldest time stamp. To find the ideal value of $K$ such that performance as compared to MVOSTM-GC does not degrade or can be increased, we perform experiments on two settings one on high contention high workload ($C_1$) and other on low contention low workload ($C_2$).

Under high contention $C_1$, each thread spawns over 100 different transactions and each transaction performs insert (45%)/delete (45%)/lookup (10%) operations over 50 random keys. And under low contention $C_2$, each thread spawns over one transaction and each transaction performs insert (45%)/delete (45%)/lookup (10%) operations over 1000 random keys. Our experiments as shown in Figure 17 give the best value of $K$ as 4 under both contention settings. These experiments are performed for list-MVOSTM and similar experiments can be performed for HT-MVOSTM. Between these two variations,
Fig. 16: Performance comparisons of variations (list-MVOSTM and list-KOSTM) of list-MVOSTM

Fig. 17: Optimal value of K as 4
KOSTM performs better than MVOSTM-GC as shown in Figure 15 and Figure 16. HT-KOSTM helps to achieve a performance speedup of 1.22 and 1.15 for workload type $W_1$ and speedup of 1.15 and 1.08 for workload type $W_2$ as compared to HT-MVOSTM and HT-MVOSTM-GC respectively. Whereas list-KOSTM (with four versions) gives a speedup of 1.1, 1.07 for workload type $W_1$ (8% insert, 2% delete and 90% look Up) and speedup of 1.25, 1.13 for workload type $W_2$ (45% insert, 45% delete and 10% lookUp) over the list-MVOSTM and list-MVOSTM-GC respectively.

**Memory Consumption by MVOSTM-GC and KOSTM:** As depicted above KOSTM performs better than MVOSTM-GC. Continuing the comparison between the two variations of MVOSTM we chose another parameter as memory consumption. Here we test for the memory consumed by each variation algorithms in creating a version of a key. We count the total versions created, where creating a version increases the counter value by 1 and deleting a version decreases the counter value by 1. Our experiments, as shown in Figure 18, under the same contentions $C_1$ and $C_2$ show that KOSTM needs less memory space than MVOSTM-GC. These experiments are performed for list-MVOSTM and similar experiments can be performed for HT-MVOSTM.

![Fig. 18: Memory Consumption](image)

8 Conclusion and Future Work

Multi-core systems have become very common nowadays. Concurrent programming using multiple threads has become necessary to utilize all the cores present in the system effectively. But concurrent programming is usually challenging due to synchronization issues between the threads.

In the past few years, several STMs have been proposed which address these synchronization issues and provide greater concurrency. STMs hide the synchronization and communication difficulties among the multiple threads from the programmer while ensuring correctness and hence making programming easy. Another advantage of STMs is that they facilitate compositionality of concurrent programs with great ease. Different
concurrent operations that need to be composed to form a single atomic unit is achieved by encapsulating them in a single transaction.

In literature, most of the STMs are RWSTMs which export read and write operations. To improve the performance, a few researchers have proposed OSTMs [3-5] which export higher level objects operation such as hash-table insert, delete etc. By leveraging the semantics of these higher level operations, these STMs provide greater concurrency. On the other hand, it has been observed in STMs and databases that by storing multiple versions for each t-object in case of RWSTMs provides greater concurrency [9, 16].

This paper presents the notion of multi-version object STMs and compares their effectiveness with single version object STMs and multi-version read-write STMs. We find that multi-version object STM provides a significant benefit over both of these for different types of workloads. Specifically, we have evaluated the effectiveness of MVOSTM for the list and hash-table data structure as list-MVOSTM and HT-MVOSTM. Experimental results of list-MVOSTM provide almost two to twenty fold speedup over existing state-of-the-art list based STMs (Trans-list, Boosting-list, NOrec-list, list-MVTO, and list-OSTM). Similarly, HT-MVOSTM shows a significant performance gain of almost two to nineteen times better than existing state-of-the-art hash-table based STMs (ESTM, RWSTMs, HT-MVTO, and HT-OSTM).

HT-MVOSTM and list-MVOSTM and use unbounded number of versions for each key. To limit the number of versions, we develop two variants for both hash-table and list data-structures: (1) A garbage collection method in MVOSTM to delete the unwanted versions of a key, denoted as MVOSTM-GC. (2) Placing a limit of $k$ on the number versions in MVOSTM, resulting in KOSTM. Both these variants gave a performance gain of over 15% over MVOSTM.

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Appendix

A  Detailed Pcode of MVOSTM

A.1  Global DS

```c
struct G_node{
    int G_key;
    struct G_vl;
    G_lock;
    node G_knext;
};

struct G_vl{
    int G_ts;
    int G_val;
    bool G_mark;
    /* rv1 stands for return value list */
    int G_rvl[];
    vl G_vnext;
};
```

A.2  Local DS

```c
class L_txlog{
    int L_tid;
    STATUS L_tx_status;
    vector <L_rec> L_list;
    find();
    getList();
};

class L_rec{
    int L_obj_id;
    int L_key;
    int L_val;
    node* L_knext, G_pred, G_curr, node;
    STATUS L_op_status;
    OP_NAME L_opn;
    getOpn();
    getKey&Objid();
    setVal();
    setOpn();
};
```

enum OP_NAME = {INSERT, DELETE, LOOKUP}
enum STATUS = {ABORT = 0, OK, FAIL, COMMIT}
| Functions          | Description                        |
|--------------------|------------------------------------|
| setOpn()           | set method name into transaction local log |
| setVal()           | set value of the key into transaction local log |
| setOpStatus()      | set status of method into transaction local log |
| setPred&Curr()     | set location of $G_{pred}$ and $G_{curr}$ according to the node corresponding to the key into transaction local log |
| getOpn()           | get method name from transaction local log |
| getVal()           | get value of the key from transaction local log |
| getOpStatus()      | get status of the method from transaction local log |
| getKey&Objid()     | get key and objid corresponding to the method from transaction local log |
| getPred&Curr()     | get location of $G_{preds}$ and $G_{currs}$ according to the node corresponding to the key from transaction local log |

Table 1: Description of accessing transaction local log methods

| p/q         | STM insert() | STM delete() | STM lookup() | STM tryC() |
|-------------|--------------|--------------|--------------|------------|
| STM insert()| +            | +            | +            | +          |
| STM delete()| +            | +            | +            | -          |
| STM lookup()| +            | +            | +            | -          |
| STM tryC()  | +            | -            | -            | -          |

Table 2: Commutative table

**Algorithm 6** STM init(): This method invokes at the start of the STM system. Initialize the global counter ($G_{cnt}$) as 1 at Line 55 and return it.

```plaintext
53 procedure STM INIT($G_{cnt}$ ↑)
54 /* Initializing the global counter */
55 $G_{cnt}$ ← 1;
56 return ($G_{cnt}$);
57 end procedure
```
Algorithm 7 STM begin(): It invoked by a thread to being a new transaction \( T_i \). It creates transaction local log and allocate unique id at Line 91 and Line 93 respectively.

```plaintext
procedure STM BEGIN(G_cnt ↓, L_fd ↑)
    /* Creating a local log for each transaction */
    L_txlog ← create new L_txlog();
    /* Getting transaction id (L_fd) from G_cnt */
    L_txlog.L_fd ← G_cnt;
    /* Incremented global counter atomically */
    G_cnt ← get&inc(G_cnt ↓); // Φlp(LinearizationPoint)
    return (L_fd);
end procedure
```

Algorithm 8 STM insert() : Optimistically, the actual insertion will happen in the STM tryC() method. First, it will identify the node corresponding to the key in local log. If the node exists then it just update the local log with useful information like value, operation name and status for the node corresponding to the key at Line 105, Line 106 and Line 107 respectively for later use in STM tryC(). Otherwise, it will create a local log and update it.

```plaintext
procedure STM INSERT(L_fd ↓, L_obj_id ↓, L_key ↓, L_val ↓)
    /* First identify the node corresponding to the key into local log using find() function */
    if (!L_txlog.find(L_fd ↓, L_obj_id ↓, L_key ↓, L_rec ↑)) then
        /* Create local log record and append it into increasing order of keys */
        L_rec ← create new L_rec(L_obj_id, L_key);
    end if
    /* Updating the local log */
    L_rec.setVal(L_obj_id ↓, L_key ↓, L_val ↓); // Φlp(LinearizationPoint)
    L_rec.setOpn(L_obj_id ↓, L_key ↓, INSERT ↓);
    L_rec.setOpStatus(L_obj_id ↓, L_key ↓, OK ↓);
    return (void);
end procedure
```
Algorithm 9  STM lookup(): If STM lookup() is not the first method on a particular key means if its a subsequent method of the same transaction on that key then first it will search into the local log from Line 112 to Line 123. If the previous method on the same key of same transaction was insert or lookup (from Line 116 to Line 118) then STM lookup() will return the value and operation status based on previous operation value and status. If the previous method on the same key of same transaction was delete (from Line 120 to Line 122) then STM lookup() will return the value and operation status as NULL and FAIL respectively. If STM lookup() is the first method on that key (from Line 125 to Line 131) then it will identify the location of node corresponding to the key in underlying DS with the help of list lookup() inside the commonLu&Del() method at Line 126.

```
procedure STM_LOOKUP(L.tid ↓, L.objid ↓, L.key ↓, L.val ↑, L.op_status ↑)
    /* First identify the node corresponding to the key into local log */
    if (L.txlog.find(L.tid ↓, L.objid ↓, L.key ↓, L.rec ↑)) then
        /* Getting the previous operation’s name */
        L.opn ← L.rec.getOpn(L.objid ↓, L.key ↓);
        /* If previous operation is insert/lookup then get the value/op_status based on the previous operations value/op_status */
        if ((INSERT = L.opn) || (LOOKUP = L.opn)) then
            L.val ← L.rec.getVal(L.objid ↓, L.key ↓);
            L.op_status ← L.rec.L_getOpStatus(L.objid ↓, L.key ↓);
            /* If previous operation is delete then set the value as NULL and op_status as FAIL */
        else if (DELETE = L.opn) then
            L.val ← NULL;
            L.op_status ← FAIL;
        end if
        /* Common function for rv_method, if node corresponding to the key is not part of local log */
        commonLu&Del(L.tid ↓, L.objid ↓, L.key ↓, L.val ↑, L.op_status ↑);
    end if
    /* Update the local log */
    L.rec.setOpn(L.objid ↓, L.key ↓, LOOKUP ↓);
    L.rec.setOpStatus(L.objid ↓, L.key ↓, L.op_status ↓);
    return ⟨L.val, L.op_status⟩;
end procedure
```
Algorithm 10  STM delete() : It will work same as a STM lookup(). If it is not the first method on a particular key means if its a subsequent method of the same transaction on that key then first it will search into the local log from Line 135 to Line 156. If the previous method on the same key of same transaction was insert (from Line 139 to Line 143) then STM delete() will return the value based on previous operation value and status as OK and set the value and operation as NULL and DELETE respectively. If previous method on the same key of same transaction was delete (from Line 145 to Line 148) then STM delete() will return the value and operation status as NULL and FAIL respectively. If previous method on the same key of same transaction was lookup (from Line 149 to Line 154) then STM delete() will return the value and operation status based on the previous operation value. If STM delete() is the first method on that key (from Line 157 to Line 163) then it will identify the location of node corresponding to the key in underlying DS with the help of list lookup() inside the commonLu&Del() method at Line 158.

```
procedure STM DELETE(L_tid ↓, L_obj_id ↓, L_key ↓, L_val ↑, L_op_status ↑)

  /* First identify the node corresponding to the key into local log */
  if (L_txlog.find(L_tid ↓, L_obj_id ↓, L_key ↓, L_rec ↑)) then
    /* Getting the previous operation’s name */
    L_opn ← L_rec.getOpn(L_obj_id ↓, L_key ↓);
    /* If previous operation is insert then get the value based on the previous operations value and set the value and operation name as NULL and DELETE respectively */
    if (INSERT = L_opn) then
      L_val ← L_rec.getVal(L_obj_id ↓, L_key ↓);
      L_rec.setVal(L_obj_id ↓, L_key ↓, NULL ↓);
      L_rec.setOpn(L_obj_id ↓, L_key ↓, DELETE ↓);
      L_op_status ← OK ;
    /* If previous operation is delete then set the value as NULL */
    else if (DELETE = L_opn) then
      L_rec.setVal(L_obj_id ↓, L_key ↓, NULL ↓);
      L_val ← NULL ;
      L_op_status ← FAIL ;
    else
      /* If previous operation is lookup then get the value based on the previous operations value and set the value and operation name as NULL and DELETE respectively */
      L_val ← L_rec.getVal(L_obj_id ↓, L_key ↓);
      L_rec.setVal(L_obj_id ↓, L_key ↓, NULL ↓);
      L_rec.setOpn(L_obj_id ↓, L_key ↓, DELETE ↓);
      L_op_status ← L_rec.getOpStatus(L_obj_id ↓, L_key ↓);
    end if
  else
    /* Common function for rv_method, if node corresponding to the key is not part of local log */
    commonLu&Del(L_tid ↓, L_obj_id ↓, L_key ↓, L_val ↑, L_op_status ↑);
  end if

  /* Update the local log */
  L_rec.setOpn(L_obj_id ↓, L_key ↓, DELETE ↓);
  L_rec.setOpStatus(L_obj_id ↓, L_key ↓, L_op_status ↓);
  return (L_val, L_op_status);
end procedure
```
Fig. 19: Need of inserting 0th version by rv_method to satisfy opacity
Algorithm 11  commonLukDel() : This method is invoked by a rv_method (STM lookup() and STM delete()), if node corresponding to the key is not part of local log. At Line [167] it identify the G_preds[] and G_carrs[] for the node corresponding to the key in underlying DS with the help of list_Lookup(). If node corresponding to the key is in BL of underlying DS then (from Line [169] to Line [181]) it finds the version tuple corresponding to the key which is having the largest timestamp less than itself as closest_tuple at Line [171]. After that, it will add itself into closest_tuple.rvl at Line [173]. If identified version mark field is TRUE then it will set the L_op_status and L_val as FAIL and NULL otherwise, OK and value of identified tuple from Line [175] to Line [181] respectively. If node corresponding to the key is in RL of underlying DS then (from Line [183] to Line [195]) it finds the version tuple corresponding to the key which is having the largest timestamp less than itself as closest_tuple at Line [185] After that, it will add itself into closest_tuple.rvl at Line [187]. If identified version mark field is TRUE then it will set the L_op_status and L_val as FAIL and NULL otherwise, OK and value of identified tuple from Line [189] to Line [195] respectively. If node corresponding to the key is not part of underlying DS then (from Line [197] to Line [205]) it will create the new node corresponding to the key and add it into RL of underlying DS with the help of list_Destroy() at Line [198]. After that it creates the 0th version (at Line [200]) and add itself into 0th_rvl at Line [201]. Then, it will set the L_op_status and L_val as FAIL and NULL respectively at Line [203] and Line [204]. Finally, it will release the lock which is acquired in list_Lookup() at Line [205] and update the local log to help the upcoming method of the same transaction on the same key. Why do we need to create a 0th version by rv_method in RL? This will be clear by the Figure 19 where we have two concurrent transactions T1 and T2. History in the Figure 19(a) is not opaque because we can’t come up with any serial order. To make it serial (or opaque) first method lu2(ht, k3, NULL) of transaction T2 have to create the 0th version in RL if its not present in the underlying DS and add itself into 0th_rvl. So in future if any lower timestamp transaction less than T2 will come then that lower transaction will ABORT (in this case transaction T1 is aborting in (Figure 19(b))) because higher timestamp already present in the rvl (Figure 19(c)) of the same version. After aborting T1 we will get the serial history.

```c
procedure COMMONLukDel(L_id ↘, L_obj_id ↘, L_key ↘, L_val ↗, L_op_status ↗)
/* If node corresponding to the key is not present in local log then search into underlying DS with the help of list_Lookup */
list_Lookup(L_obj_id ↘, L_key ↘, G_preds ↗, G_carr ↗);
/* If node corresponding to the key is part of BL */
if (carrs[1], key = L_key) then
  /* From carrs[1].els, identify the right version_tuple */
  find_lts(L_id ↘, carrs[1] ↘, closest_tuple ↗);
  /* Closest_tuple is (j, val, mark, rvl, vnex) */
  Adding L_id into j’s rvl;
  /* If the closest_tuple mark field is TRUE then L_op_status and L_val set as FAIL and NULL otherwise set OK and value of closest_tuple respectively */
  if (closest_tuple.mark = TRUE) then
    L_op_status ← FAIL;
    L_val ← NULL;
  else
    L_op_status ← OK;
    L_val ← closest_tuple.val;
end if
/* If node corresponding to the the key is part of RL */
else if (carrs[0], key = L_key) then
  /* From carrs[0].els, identify the right version_tuple */
  find_lts(L_id ↘, carrs[0] ↘, closest_tuple ↗);
  /* Closest_tuple is (j, val, mark, rvl, vnex) */
```
Adding $L_jid$ into j’s rvl:

/* If the closest_tuple mark field is TRUE then $L_{op\_status}$ and $L_{val}$ set as FAIL and NULL otherwise set OK and value of closest_tuple respectively */

if (closest_tuple.mark = TRUE) then
    $L_{op\_status} \leftarrow$ FAIL ;
    $L_{val} \leftarrow$ NULL ;
else
    $L_{op\_status} \leftarrow$ OK ;
    $L_{val} \leftarrow$ closest_tuple.val ;
end if

else
    /* If node corresponding to the key is not part of RL as well as BL then create the node into RL with the help of list_ins() */
    list_ins(G_pred ↓, G_curr ↓, node ↑) ;
    /* Insert the 0th version tuple */
    insert v_tuple(0, NULL, T, NULL, NULL) into node.vl in the increasing order;
    Adding $L_jid$ into 0th rvl;
    /* Setting $L_{op\_status}$ and $L_{val}$ as FAIL and NULL because its reading from the marked version, which is TRUE */
    $L_{op\_status} \leftarrow$ FAIL ;
    $L_{val} \leftarrow$ NULL ;
end if

/* Releasing the locks in increasing order */
releasePred&CurrLocks(G_preds[] ↓, G_currs[] ↓) ;
/* Create local log record and append it into increasing order of keys */
$L_{rec} \leftarrow$ Create new $L_{rec}$($L_{obj\_id}$, $L_{key}$) ;
$L_{rec}.setVal$($L_{obj\_id}$ ↓, $L_{key}$ ↓, $L_{val}$ ↓) ;
$L_{rec}.setPred&Curr$($L_{obj\_id}$ ↓, $L_{key}$ ↓, G_pred ↓, G_curr ↓) ;
return ($L_{val}$, $L_{op\_status}$) ;

end procedure
Algorithm 12 STM tryC() : The actual effect of upd_methods (STM insert() and STM delete()) will take place in STM tryC() method. From Line 215 to Line 231 will identify and validate the G_preds[] and G_curs[] of each upd_method of same transaction. At Line 223 it will validate if there exist any higher timestamp transaction in the rvl of the closest tuple of curs[1] then returns ABORT at Line 224. Same as at Line 225 it will validate if there exist any higher timestamp transaction in the rvl of the closest tuple of curs[0] then returns ABORT at Line 227. Otherwise it will perform the above steps for remaining upd_methods. On successful validation of all the upd_methods, the actually effect will be taken place from Line 233 to Line 259. If the upd_method is insert and node corresponding to the key is part of BL then it creates the new version tuple and add it in increasing order of version list from Line 240 to Line 242. If node corresponding to the key is part of RL then it adds the same node in the BL as well with the help of list_Inst() at Line 244 and creates the new version tuple and add it in increasing order of version list from Line 243 to Line 245. Otherwise it will create the node and insert it into BL with the help of list_Inst() and insert the version tuple from Line 246 to Line 250. If the upd_method is delete and node corresponding to the key is part of BL then it creates the new version tuple and set its mark field as TRUE and add it in increasing order of version list from Line 252 to Line 256. After successful completion of each upd_method, it will validate the G_preds[] and G_curs[] of upcoming upd_method of the same transaction with the help of intraTransValidation() at Line 258. Eventually, it will release all the locks at Line 261 in the same order of lock acquisition.

procedure STM TRYC(L_id↓, L_status↑)
/* Get the local log list corresponding to each transaction which is in increasing order of keys */
  L_list ← L_xlog.getList(L_id↓);
/* Identify the new G_preds[] and G_curs[] for all update methods of a transaction and validate it */
  while (L_rec_i ← next(L_list)) do
    (L_key, L_obj_id) ← L_rec_i.getKey&Objid(L_rec_i↓);
    /* Identify the new G_pred and G_cur with the help of list_lookup() */
    list_lookup(L_obj_id↓, L_key↓, G_pred↑, G_curr↑);
    if ((curs[1].key = L_key)&(check_versions(L_id↓, curs[1]↓) = FALSE)) then
      Unlock all the variables;
      return ABORT;
    else if ((curs[0].key = L_key)&(check_versions(L_id↓, curs[0]↓) = FALSE)) then
      Unlock all the variables;
      return ABORT;
  end if;
/* Update the log entry */
  L_rec_i.setPred&Cur(L_obj_id↓, L_key↓, G_pred↓, G_curr↓);
end while
/* Get each update method one by one and take effect in underlying DS */
while (L_rec_i ← next(L_list)) do
  (L_key, L_obj_id) ← L_rec_i.getKey&Objid(L_rec_i↓);
  /* Get the operation name from local log record */
  L_opn ← (L_rec_i), L_opn;
  /* Modify the G_preds[] and G_curs[] for the consecutive update methods which are working on overlapping zone in lazy-list */
  intraTransValidation(L_rec_i↓, G_preds[]↑, G_curs[]↑);
  /* If operation is insert then after successful completion of it node corresponding to the key should be part of BL */
if (INSERT = L_opn) then
    if (currs[1].key = L_key) then
        insert v_tuple(L_tid, val, F, NULL, NULL) into G_curr.vl in the increasing order;
    else if (currs[0].key = L_key) then
        list_Init(G_pred ↓, G_curr ↓, node ↑)
        insert v_tuple(L_tid, val, F, NULL, NULL) into G_curr.vl in the increasing order;
    else
        /* If node corresponding to the key is not part underlying DS then
            create the node with the help of list_Init() and insert it into BL */
        list_Init(G_pred ↓, G_curr ↓, node ↑);
        insert v_tuple(L_tid, NULL, T, NULL, NULL) into node.vl in the increasing order;
    end if
else if (DELETE = L_opn) then
    /* If node corresponding to the key is part of BL */
    if (currs[1].key = L_key) then
        insert v_tuple(L_tid, NULL, T, NULL, NULL) into G_curr.vl in the increasing order;
    end if
end if
end while
releaseOrderedLocks(L_list ↓);
/* Set the transaction status as OK */
L_tx_status ← OK;
return (L_tx_status);
end procedure

Algorithm 13  list_del() : Delete a node from blue link in underlying hash table at location corresponding to G_preds[] & G_currs[].
Algorithm 14 list_lookup(): This method is called by rv_method and upd_method. It finds the location of the node corresponding to the key in underlying DS from Line 275 to Line 295. First it identifies the node in BL (from Line 275 to Line 285) then in RL (from Line 288 to Line 295). After finding the appropriate location of the node corresponding to the key in the form of $G_{preds}[]$ and $G_{curs}[]$, it will acquire the locks on it at Line 297 and validate it at Line 299.

```
procedure LIST_LOOKUP(L_obj_id ↓, L_key ↓, G_preds[] ↑, G_curs[] ↑)
/* By default setting the L_op_status as RETRY */
STATUS L_op_status ← RETRY;
/* Identify the G_preds[] and G_curs[] for node corresponding to the key if
 L_op_status is RETRY */
while (L_op_status = RETRY) do
  /* Get the head of the bucket in chaining hash-table with the help of L_obj_id
 and L_key */
  G_head ← get_list_head(L_obj_id ↓, L_key ↓);
  /* Initialize preds[0] to head */
  preds[0] ← G_head;
  /* Initialize currs[1] to preds[0].BL */
  currs[1] ← preds[0].BL;
  /* Searching node corresponding to the key into BL */
  while ((currs[1].key) < L_key) do
    preds[0] ← currs[1];
    currs[1] ← currs[1].BL;
  end while
  /* Initialize preds[1] to head */
  preds[1] ← preds[0];
  /* Initialize currs[0] to preds[1].RL */
  currs[0] ← preds[1].RL;
  /* Searching node corresponding to the key into RL */
  while ((currs[0].key) < L_key) do
    preds[1] ← currs[0];
    currs[0] ← currs[0].RL;
  end while
  /* Acquire the locks on increasing order of keys */
  acquirePredC & CurrLocks(G_preds[] ↓, G_curs[] ↓);
  /* Method validation to identify the changes done by concurrent conflicting
 method */
  methodValidation(G_preds[] ↓, G_curs[] ↓, L_op_status ↑);
  /* If L_op_status is RETRY then release all the locks */
  if (L_op_status = RETRY) then
    releasePredC & CurrLocks(G_preds[] ↓, G_curs[] ↓);
  end if
end while
return (G_preds[], G_curs[]);
end procedure
```
Algorithm 15  acquirePred&CurrLocks() : acquire all locks taken during list_lookup().

function ACQUIREPRED&CURRLOCKS(G_pret[] ↓, G_curt[] ↓)

preds[0].lock();
preds[1].lock();
curt[0].lock();
curt[1].lock();
return (void);
end function

Algorithm 16  releasePred&CurrLocks() : Release all locks taken during list_lookup().

function RELEASEPRED&CURRLOCKS(G_pret[] ↓, G_curt[] ↓)
preds[0].unlock();//
preds[1].unlock();
curt[0].unlock();
curt[1].unlock();
return (void);
end function
**Algorithm 17**  
**list**_Ins(): This method is called by the **rv**_method and **upd**_method.

Color of **preds** & **currs** depicts the red or blue node.

```plaintext
// Inserting the node from redlist to bluelist */
if (list_type = (RL, BL)) then

currs[0].BL ← currs[1];
preds[0].BL ← currs[0];
/* Inserting the node into redlist only */
else if (list_type = RL) then

node ← Create new node();
/* After created the node acquiring the lock on it */
node.RL ← currs[0];
preds[1].RL ← node;
else
/* Inserting the node into red as well as blue list */
node ← new node();
/* After creating the node acquiring the lock on it */
node.RL ← currs[0];
node.BL ← currs[1];
preds[1].RL ← node;
preds[0].BL ← node;
end if
return ⟨node⟩;
end procedure
```

---

Fig. 20: Validation by check_version

(a) Opaque history: \( T_1 \) Abort

(b) Underlying Data structure(DS)
**Algorithm 18** `find_lts()`: This method is called by `rv_method` and `upd_method` to identify a `closest_tuple ⟨j, val, mark, rel, vnext⟩` created by the transaction `T_j` with the largest timestamp smaller than `L_j.id` from Line 349 to Line 354.

```plaintext
procedure FIND_LTS(L_j.id ↓, G_currs[] ↓, closest_tuple ↑)
  /* Initialize closest_tuple */
  closest_tuple = ⟨0, NULL, F, NULL, NULL⟩;
  /* For all the version of G_currs[] identify the largest timestamp less than L_j.id */
  for all ⟨p, val, mark, rvl, vnext⟩ ∈ G_currs[].vl do
    if (p < L_j.id) and (closest_tuple.ts < p) then
      /* Assign closest tuple as ⟨p, val, mark, rvl, vnext⟩, if any version tuple is having largest timestamp less then L_j.id exist */
      closest_tuple = ⟨p, val, mark, rvl, vnext⟩;
      end if
    end for
  return ⟨closest_tuple⟩;
end procedure
```

Algorithm 19 `check_versions()`: This method is called by the STM `tryC()`. First it will find the `closest_tuple ⟨j, val, mark, rel, vnext⟩` created by the transaction `T_j` with the largest timestamp smaller than `L_j.id` at Line 359. Then, it checks the version list to identify is there any higher timestamp already present in the `rvl` of `closest_tuple` from Line 361 to Line 367. If it presents then it will return `FALSE` at Line 365 otherwise, `TRUE` at Line 369. It will be more clear by the Figure 20(a) where second method `ins_1(ht, k3, ABORT)` of transaction `T_1` will ABORT because higher transaction `T_2` timestamp is already present in the `rvl` of `closest_tuple` as 0th version in Figure 20(b).

```plaintext
procedure CHECK_VERSIONS(L_j.id ↓, G_currs[] ↓)
  /* From G_currs[].vls, identify the correct version tuple means identify the tuple which is having higher time-stamp but less then it */
  find_lts(L_j.id ↓, G_currs[] ↓, closest_tuple ↑);
  /* Got the closest tuple as (j, val, mark, rvl, vnext) */
  for all T_k in rvl of closest_tuple.j do
    /* T_k has already read the version created by T_j */
    if (L_j.id < k) then
      /* If in rvl of closest_tuple.j, any higher time-stamp exists then L_j.id then return FALSE */
      return ⟨FALSE⟩;
      end if
    end for
    /* If in rvl of closest_tuple.j, there is no higher time-stamp exists then L_j.id then return TRUE */
    return ⟨TRUE⟩;
  end procedure
```
Algorithm 20  methodValidation() : This method is called by the rv_method and upd_method. It will identify the conflicts among the concurrent methods of different transactions at Line 373. It will be more clear by the Figure 21 where two concurrent conflicting methods of different transactions are working on the same key \( k_3 \). Initially, at stage \( s_1 \) in Figure 21(c) both the conflicting method optimistically (without acquiring locks) identify the same \( G_{\text{preds}}[\cdot] \) and \( G_{\text{currs}}[\cdot] \) for key \( k_3 \) from underlying DS in Figure 21(a). At stage \( s_2 \) in Figure 21(c), method \( \text{ins}_1(k_3) \) of transaction \( T_1 \) acquired the lock on \( G_{\text{preds}}[\cdot] \) and \( G_{\text{currs}}[\cdot] \) and inserted the node into it (Figure 21(b)). After successful insertion by \( T_1 \), \( G_{\text{preds}}[\cdot] \) and \( G_{\text{currs}}[\cdot] \) will change for \( \text{lu}_2(k_3) \) at stage \( s_3 \) in Figure 21(c). It will caught via method validation function at Line 373 when \( (G_{\text{preds}}[\cdot].BL \neq G_{\text{currs}}[\cdot]) \) for \( \text{lu}_2(k_3) \). After that again it will find the new \( G_{\text{preds}}[\cdot] \) and \( G_{\text{currs}}[\cdot] \) for \( \text{lu}_2(k_3) \) with the help of listLookup() method and eventually it will commit.

371: procedure methodValidation(G_prels[\cdot] ↓, G_currs[\cdot] ↓, L_op_status ↑)
372: /* Validating G_prels[\cdot] and G_currs[\cdot] */
373: if \((\text{predis}[0].\text{marked})||\text{currs}[1].\text{marked})||\text{predis}[0].\text{BL} \neq \text{currs}[0])\) then
374: /* If validation fail then L_op_status set as RETRY */
375: L_op_status ← RETRY
376: else
377: L_op_status ← OK
378: end if
379: return (L_op_status) ;
380: end procedure
Algorithm 21 \(L_{\text{find}}()\): This method is called by STM insert(), rv_method and upd_method. It will check whether any method corresponding to \((L_{\text{obj id}}, L_{\text{key}})\) is present in local log from Line 384 to Line 389.

```plaintext
procedure L_FIND(L_{\text{id}} \downarrow, L_{\text{obj id}} \downarrow, L_{\text{key}} \downarrow, L_{\text{rec}} \uparrow)
L_list \leftarrow L_{\text{txlog}.get List(L_{\text{id}} \downarrow)};

/* Every method first identify the node corresponding to the key into local log */
while (L_{\text{rec}_i} \leftarrow next(L_{\text{list}}))
do
   /* Taking one by one L_{\text{obj id}} and L_{\text{key}} form L_{\text{rec}} */
   if ((L_{\text{rec}_i}.first = L_{\text{obj id}}) & (L_{\text{rec}_i}.sec = L_{\text{key}})) then
      return \(\langle \text{TRUE}, L_{\text{rec}} \rangle\);
   end if
end while
return \(\langle \text{FALSE}, \text{NULL} \rangle\);
end procedure
```

Algorithm 22 releaseOrderedLocks(): Release all locks in increasing order of their keys from Line 394 to Line 397.

```plaintext
procedure RELEASEORDEREDLOCKS(L_{\text{list}} \downarrow)
/*Releasing all the locks in increasing order of the keys */
while (L_{\text{rec}_i} \leftarrow next(L_{\text{list}})) do
   L_{\text{rec}_i}.G_{\text{preds}}[].unlock() //\(\Phi_{\text{tp}}\)
   L_{\text{rec}_i}.G_{\text{currs}}[].unlock();
end while
return (void);
end procedure
```

Fig. 22: Intra transaction validation
Algorithm 23 intraTransValidation() : This method is called by STM tryC() only. If two upd_methods within same transaction have at least one shared node among its recorded $G_{preds}$ and $G_{currs}$, in this case the previous upd_method effect might be overwritten if the next upd_method $G_{preds}$ and $G_{currs}$ are not updated according to the updates done by the previous upd_method. Thus to solve this we have intraTransValidation() after each upd_method in STM tryC(). This will be more clear by the Figure 22 where two upd_methods of same transaction $T_1$ are $ins_{11}(k_3)$ and $ins_{12}(k_5)$ (Figure 22(c)). At stage $s_1$ in Figure 22(c) both the upd_methods identify the same $G_{preds}$ and $G_{currs}$ from underlying DS (Figure 22(a)). After the successful insertion done by first upd_method at stage $s_2$ in Figure 22(c), key $k_3$ is part of underlying DS (Figure 22(b)). At stage $s_3$ in Figure 22(c) if we will not update the $G_{preds}$ and $G_{currs}$ for $ins_{12}(k_5)$ then it will overwrite the previous method updates. To resolve this issue we are doing the intraTransValidation() after each upd_method to assign the appropriate $G_{preds}$ and $G_{currs}$ for the upcoming upd_method of same transaction.

400: procedure INTRA_TRANSVALIDATION($L_{rec} \downarrow, G_{preds} \uparrow, G_{currs} \uparrow$)
401: $L_{rec}.getAllPreds&Currs(L_{rec} \downarrow, G_{preds} \uparrow, G_{currs} \uparrow)$;
402: /* if $preds[0]$ is marked or $currs[1]$ is not reachable from $preds[0].BL$ then modify the next consecutive upd_method $preds[0]$ based on previous upd_method */
403: if (($preds[0].marked$ $\lor$ $preds[0].BL \neq currs[1]$) then
404: /* find $k_1$ such that $le_k$ contains previous update method on same bucket */
405: if ($L_{rec}.opn$ = INSERT) then
406: $L_{rec}.preds[0].unlock()$;
407: $preds[0] \leftarrow (L_{rec}.preds[0].BL)$;
408: $L_{rec}.preds[0].lock()$;
409: else
410: /* upd_method method $preds[0]$ will be previous method $preds[0]$ */
411: $L_{rec}.preds[0].unlock()$;
412: $preds[0] \leftarrow (L_{rec}.preds[0])$;
413: $L_{rec}.preds[0].lock()$;
414: end if
415: end if
416: /* if $currs[0]$ & $preds[1]$ is modified by prev operation then update them also */
417: if ($preds[1].RL \neq currs[0]$) then
418: $L_{rec}.preds[1].unlock()$;
419: $preds[1] \leftarrow (L_{rec}.preds[1].RL)$ ;
420: $L_{rec}.preds[1].lock()$;
421: end if
422: return ($G_{preds}$, $G_{currs}$);
B Garbage Collection

We have performed garbage collection method to delete the unwanted version of keys i.e. if the particular version corresponding to any key is not going to use in future then we can delete that version. For the better understanding of it please consider Figure 23. Here, we are having 3 versions of key $k_1$ with timestamp 0, 15 and 25 respectively. Each version is having 5 fields described in Section 4. Now, consider the version 15, there exist the next version 25 and all the transactions between 15 to 25 has been terminated (either commit or abort) then we are deleting version 15. Similarly, we can delete other versions corresponding to each key as well and optimize the memory.

![Data Structures for Garbage Collection](image)

**Fig. 23: Data Structures for Garbage Collection**

**Algorithm 24 STM**

```plaintext
procedure STM BEGIN($L_t_id$)
    /*Creating a local log for each transaction*/
    $L_tlog$ ← create new $L_tlog$;
    /*Get $t_id$ from $G_cnt$*/
    $L_tlog.L_t_id$ ← $G_cnt$;
    /*Incremented $G_cnt$*/
    $G_cnt$ ← get&inc($G_cnt$);
    liveList.lock();
    add $L_t_id$ to liveList;
    liveList.unlock();
    return ($L_t_id$);
end procedure
```
Algorithm 25 \texttt{ins\_tuple()}: Inserts the version tuple for \((L\_id, v)\) created by the transaction \(T_i\) into the version list of \(L\_key\)

\begin{verbatim}
procedure INS\_TUPLE(L\_key ⊲, L\_id ⊲, v ⊲, NULL ⊲, NULL ⊲) /*Initialize cur\_tuple*/
cur\_tuple = ⟨L\_id, val, F, NULL, NULL⟩;
/* Finds the tuple with the largest timestamp smaller than i */
find\_lts(L\_id ⊲, L\_key ⊲, prev\_tuple ↑);
/*prev\_tuple is ⟨ts, val, mark, rel, nts⟩*/
cur\_tuple.nts = prev\_tuple.nts;
prev\_tuple.nts = L\_id;
insert cur\_tuple into L\_key.vl in the increasing order of timestamps;
/* |L\_key.vl| denotes number of versions of L\_key created and threshold is a predefined value. */
if (|L\_key.vl| > threshold) then
    /*If number of created versions for L\_key crossed the threshold value then calling the Garbage Collection*/
gc(L\_key);
end if
return (void)
end procedure
\end{verbatim}
Algorithm 26 STM gc(): Unused version of a t-object $L_{key}$ will be deleted from $L_{key}.vl$

```plaintext
452: procedure GC($L_{key} \downarrow$)
453:   liveList.lock();
454:   /*t-object $L_{key}$ is already locked*/
455:   for all (cur_tuple $\in L_{key}.vl$) do
456:     if (cur_tuple.nts == NULL) then
457:       /* If nts is NULL, check the next tuple in the version list */
458:       continue;
459:     end if
460:     $j = cur_tuple.ts + 1$;
461:     /*Check for all ids $j$ in the range $j < nts$*/
462:     while ($j < cur_tuple.nts$) do
463:       if ($j \in liveList$) then
464:         /* If any tuples with timestamp $j$, such that $i < j < nts$ have not terminated (means exist in liveList) then cur_tuple can’t be deleted*/
465:         break;
466:       end if
467:     end while
468:     /* If all the tuples with timestamp $j$, such that $i < j < nts$ have terminated then cur_tuple can be deleted*/
469:     delete cur_tuple;
470:   end for
471:   /* liveList is not unlocked when this function returns */
472:   return ⟨void⟩
473: end procedure
```