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To cite this version:
Matthieu Nicolas, Gérald Oster, Olivier Perrin. Efficient Renaming in Sequence CRDTs. PaPoC 2020 - 7th Workshop on Principles and Practice of Consistency for Distributed Data, Apr 2020, Heraklion / Virtual, Greece. hal-02526724v2

HAL Id: hal-02526724
https://inria.hal.science/hal-02526724v2
Submitted on 10 Apr 2020

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Efficient Renaming in Sequence CRDTs

Matthieu Nicolas  
matthieu.nicolas@loria.fr  
Université de Lorraine, CNRS, Inria,  
LORIA, F-54500  
Nancy, France

Gérald Oster  
gerald.oster@loria.fr  
Université de Lorraine, CNRS, Inria,  
LORIA, F-54500  
Nancy, France

Olivier Perrin  
olivier.perrin@loria.fr  
Université de Lorraine, CNRS, Inria,  
LORIA, F-54500  
Nancy, France

Abstract
To achieve high availability, large-scale distributed systems have to replicate data and to minimise coordination between nodes. Literature and industry increasingly adopt Conflict-free Replicated Data Types (CRDTs) to design such systems. CRDTs are data types which behave as traditional ones, e.g. the Set or the Sequence. However, unlike traditional data types, they are designed to natively support concurrent modifications. To this end, they embed in their specification a conflict-resolution mechanism.

To resolve conflicts in a deterministic manner, CRDTs usually attach identifiers to elements stored in the data structure. Identifiers have to comply with several constraints, such as uniqueness or belonging to a dense order. These constraints may hinder the identifiers’ size from being bounded. As the system progresses, identifiers tend to grow. This inflation deepens the overhead of the CRDT over time, leading to performance issues.

To address this issue, we propose a new CRDT for Sequence which embeds a renaming mechanism. It enables nodes to reassign shorter identifiers to elements in an uncoordinated manner. Experimental results demonstrate that this mechanism decreases the overhead of the replicated data structure and eventually limits it.

CCS Concepts  
• Theory of computation → Distributed algorithms;  
• Software and its engineering → Consistency;  
• Human-centered computing → Collaborative and social computing systems and tools;  
• Applied computing → Text editing;

Keywords  
CRDTs, real-time collaborative editing, eventual consistency, memory-wise optimisation, performance

1 Introduction
In order to serve an ever-growing number of users and provide an increasing volume of data, large-scale systems such as data stores or collaborative editing tools adopt the eventual consistency model [1]. This model ensures the high availability of the system, even in case of network partitions. To this end, it relaxes consistency constraints and minimises coordination between nodes. In this model, every node owns a copy of the data, can modify it and propagate the updates to others. Therefore, replicas can temporarily diverge. To ensure that nodes converge eventually despite concurrently generated updates, a conflict resolution mechanism is required.

Several approaches were introduced to design efficient conflict resolution mechanisms. The one we consider proposes to use Conflict-free Replicated Data Types (CRDTs) [2]. CRDTs are new specifications of abstract data types, e.g. the Set or the Sequence. However, when compared to former ones, they are designed to support natively concurrent modifications. To this end, they embed a conflict-resolution mechanism directly in their specification.

CRDTs appear as a keystone technology of a new paradigm of applications: Local-First Software [3]. They also have been proven a suitable approach to build distributed real-time collaborative editors [4]. Still, they exhibit some limitations. Especially in the context of real-time collaborative editing, the internal conflict resolution mechanism accumulates a large amount of metadata over time.

To address this particular issue, we propose a new CRDT for Sequence which embeds a renaming mechanism. It enables to minimise the overhead of the data structure by discarding accumulated metadata eventually.

This paper is organised as follows. Section 2 provides the background of our approach. In section 3, we introduce RenamableLogoutSplit, our new CRDT for Sequence. Section 4 presents the benchmarks we performed to evaluate our proposition and the obtained results. In section 5, we compare our approach to existing ones. Finally, section 6 concludes and introduces possible future work.

2 Background
To deterministically solve conflicts and ensure convergence of all nodes, CRDTs rely on metadata. In the context of Sequence CRDTs, two different approaches were proposed, both trying to minimise the overhead introduced. The first one [5–7] attaches fixed size identifiers to each element in the sequence and uses them to represent the sequence as a linked list. The downside of this approach is an ever growing overhead, as it needs to keep removed elements to deal with potential concurrent updates, effectively turning them into tombstones. The second one [8–10] avoids the need of tombstones by attaching identifiers from a dense totally ordered set to elements. Elements are ordered into the sequence by comparing their respective identifiers. However this approach suffers from an ever-increasing overhead, as the size of such dense totally ordered identifiers is variable and grows over time. In the context of this paper, we focus on the later approach.
2.1 LogootSplit

Proposed by André et al. [10], LogootSplit (LS) is the state of the art of the variable-size identifiers approach of Sequence CRDT. As explained previously, it uses identifiers from a dense totally ordered set to position elements into the replicated sequence.

To this end, LogootSplit generates identifiers made of a list of tuples to elements. These tuples have four components: 1. a position, which embodies the intended position of the element, 2. a node identifier, 3. a node sequence number and 4. an offset, which are combined to make identifiers unique. By comparing identifiers using the lexicographical order, LogootSplit is able to determine the position of the element relatively to others. In this paper, we represent identifiers using the following notation: \( \text{position}^\text{node id} \text{ node seq}^\text{offset} \) where position is a lowercase letter, node id an uppercase one and both node seq and offset integers.

Instead of storing an identifier for each element of the sequence, the main insight of LogootSplit is to aggregate dynamically elements into blocks. Grouping elements into blocks enables LogootSplit to assign logically an identifier to each element while effectively storing only the block length and the identifier of its first element. LogootSplit gathers elements with contiguous identifiers into a block. We call contiguous two identifiers that are identical except for their last offset, and with both offsets being consecutive. Figure 1 illustrates such a case: in Figure 1a, the element identifiers form a chain of contiguous identifiers. LogootSplit is then able to group them into one block to minimise the metadata stored, as shown in Figure 1b.

![Figure 1. Representation of a LogootSplit sequence containing the elements "HLO".](image)

This feature allows to shift the root of metadata growth from the number of elements to the number of blocks. As blocks can contain an arbitrary number of elements, it enables to reduce significantly the memory overhead of the data structure.

2.2 Limits

As stated previously, the size of identifiers from a dense totally ordered set is variable. When nodes insert new elements between two others with the same position value, LogootSplit has no other option than to increase the size of the resulting identifiers. Figure 2 illustrates such cases. In this example, since the node inserts a new element between contiguous identifiers, LogootSplit is not able to generate a fitting identifier of the same size. To comply with the intended order, LogootSplit generates a new identifier by appending a new tuple to the identifier of the predecessor.

![Figure 2. Insertion leading to longer identifiers](image)

As a result, the size of identifiers tends to grow as the collaboration progresses. This growth impacts negatively the performance of the data structure on several aspects. Since identifiers attached to values become longer, the memory overhead of the data structure increases accordingly. This also increases the bandwidth consumption as nodes have to broadcast identifiers to others.

Additionally, as the lifetime of the replicated sequence increases, the number of blocks composing it grows as well. Indeed, several constraints on identifier generation prevent nodes from adding new elements to existing blocks. For example, only the node that generated the block can append or prepend elements to it. These limitations cause the generation of new blocks. Since no mechanism to merge blocks a posteriori is provided, the sequence ends up fragmented into many blocks. The efficiency of the data structure decreases as each block introduces its own overhead.

In our benchmarks, we measure that the content eventually represents less than 1% of the data structure size, the remaining 99% being metadata. It is thus necessary to address the previously highlighted issues.

3 Proposed approach

We propose a new Sequence CRDT belonging to the variable-size identifiers approach: RenameableLogootSplit (RLS) [11].

To address the limitations of LogootSplit, we embed in the data structure a renaming mechanism. The purpose of this mechanism is to reassign shorter identifiers to elements and to group them into blocks to minimise the memory overhead of the whole sequence.

To avoid costly and blocking consensus algorithms, we instead adopt the optimistic replication [12] approach for our mechanism. Nodes perform renaming without any coordination. However, this operation is not intrinsically commutative with others. If conflicts arise, we use Operational Transformations (OT) [13, 14] to enable nodes to resolve them deterministically.
3.1 System Model

The system is composed of a dynamic set of nodes, as nodes join and leave dynamically the collaboration during its lifetime. Nodes collaborate to build and maintain a sequence using RenamableLogootSplit. Each node owns a copy of the sequence and edit it without any coordination.

Nodes communicate through a Peer-to-Peer (P2P) network, which is unreliable. Messages can be lost, re-ordered or delivered multiple times. The network is also vulnerable to partitions, which split nodes into disjoined subgroups. To overcome the failures of the network, nodes rely on a message-passing layer. As RenamableLogootSplit is built on top of LogootSplit, it shares the same requirements for the operation delivery. This layer is thus used to deliver messages to the application exactly-once. The layer also ensures that remove operations are delivered after corresponding insert operations. Nodes use an anti-entropy mechanism to synchronise in a pairwise manner, by detecting and re-exchanging lost operations.

3.2 rename operation

Our rename operation helps RenamableLogootSplit to reduce the overhead of nodes replica. This operation reassigns arbitrary identifiers to elements.

3.3 Dealing with concurrent updates

As rename operations can be issued without any kind of coordination, it is possible for other nodes to perform updates concurrently. Figure 4 illustrates such cases. In this example node B inserts the new element “L”, assigns the id \( i_{B,0} \) to it and broadcasts its update, concurrently to the rename operation described in Figure 3. Upon reception of the insert operation, node A adds the inserted element into its sequence, using the element id to determine its position. However, since identifiers were modified by the concurrent rename operation, node A inserts the new element at the end of its sequence (since \( i_{A,1} \neq i_{B,0} \)). As described by this example, applying naively concurrent updates would result in inconsistencies. It is thus necessary to handle concurrent updates to rename operations in a particular manner.

To detect them, we use an epoch-based system. We add an epoch to the sequence as a property. Each time a rename operation is applied, the sequence progresses to a new epoch. When nodes issue operations, they tag them with their current epoch. Upon the reception of an operation, nodes compare the operation epoch to their current one. If they differ, nodes have to transform the operation before applying it.

Algorithm 1 enables nodes to transform insert or remove operations against the rename one. The main idea of this algorithm is to use the predecessor of the given identifier to do so. An example of its usage is illustrated in Figure 5. This figure depicts the same scenario as in Figure 4, except
that this time node A uses Algorithm 1 to rename the concurrently generated id before inserting it in its state. The algorithm proceeds as follows. First, node A retrieves the predecessor of the given id $i^{0}_{0} m_{0} B_{0}$ in the former state: $i^{0}_{0} f^{A}_{0}$. Then it computes the counterpart of $i^{0}_{0} f^{A}_{0}$ in the renamed state: $i^{0}_{1} f^{A}_{1}$. Finally, node A prepends it to the given id to generate the renamed id: $i^{0}_{1} i^{0}_{0} m_{0} B_{0}$. By reassigning this id to the concurrently added element, node A is able to insert it in its state while preserving the intended order.

As explained in subsection 3.2, some nodes may have applied concurrent insert operations to their state before receiving a given remote rename operation. Algorithm 1 also solves this case. It allows them to eventually converge with nodes which processed the rename operations before the concurrent insert operations.

Since nodes rely on the former state to transform concurrent operations to a rename one, they have to store it. Nodes need it until each of them can no longer issue concurrent operations to the corresponding rename operation. In other words, nodes can safely garbage collect the former state once the rename operation became causally stable [15]. Meanwhile, nodes can offload it onto the disk as it is only required to handle concurrent operations.

### Algorithm 1 Rename concurrently generated identifier

```plaintext
function renameId(id, renamedBlocks, nld, nSeq)
  // id is the identifier to rename
  // renamedBlocks is the former state
  // nld is node id of the node which issued the rename op
  // nSeq is node seq of the node which issued the rename op
  length ← renamedBlocks.length
  firstId ← idBegin(renamedBlocks[0])
  lastId ← idEnd(renamedBlocks[length − 1])
  pos ← position(firstId)
  newFirstId ← new Id(pos, nld, nSeq, 0)
  newLastId ← new Id(pos, nld, nSeq, length − 1)
  if firstId < id and id < lastId then
    pred ← findPredecessor(id, renamedBlocks)
    indexOfPred ← findIndex(pred, renamedBlocks)
    newPred ← new Id(pos, nld, nSeq, indexOfPred)
    return concat(newPredecessor, id)
  else if lastId < id and id < newLastId then
    return concat(newLastId, id)
  else if newFirstId < id and id < firstId then
    predOfNewFirstId ← new Id(pos, nld, nSeq, −1)
    return concat(predOfNewFirstId, id)
  else
    return id
end function
```

4 Evaluation

4.1 Simulations and benchmarks

To validate the proposed renaming mechanism, we performed an experimental evaluation to measure its performance on several aspects: 1. the size of the data structure 2. the integration times of insert and remove operations 3. the integration time of the rename operation. In cases 1 and 2, we use LogotSplit as the baseline data structure to compare results.

Since we were not able to retrieve an existing dataset of traces of real-time collaborative editing sessions, we ran simulations to generate traces to evaluate our data structure. The scenario is as follows: several authors collaboratively write an article. Initially, they mainly insert elements into the document. A few remove operations are still issued to simulate spelling mistakes. Once the document reaches a critical length, collaborators switch to a second phase. From this point, they stop adding new content and focus on revamping existing parts instead. This is simulated by balancing the ratio between insert and remove operations. Each author has to perform a given number of operations and the collaboration ends once all of them received all operations. We take
snapshots of the document at given steps of the collaboration to measure the evolution of the document.

Simulations have been run with following experimental settings: we deployed 10 bots as separate Docker containers on a single workstation. Each container corresponds to a single mono-threaded Node.js process simulating an author. The bots share and edit collaboratively the document using either LogootSplit or RenamableLogootSplit according to the session. In both cases, each bot performs an insert or a remove operation locally every 200 ± 50ms. During the first phase, the probabilities for each operation of being an insert or a remove are respectively of 80% and 20%. Once the document reaches 60k characters (around 15 pages), bots switch to the second phase and set both probabilities to 50%. Generated operations are broadcast to other nodes using a P2P full mesh network. After issuing an operation, there are 5% of chances that the bot moves its cursor to another position in the document. Each bot performs 15k operations. Snapshots are taken every 10k operations overall. Additionally, in the case of RenamableLogootSplit, one bot is arbitrarily designated as the master. It performs rename operations every 30k operations overall.

Convergence Using the generated snapshots, we compare the final content of nodes per session. In this way, we can confirm that nodes eventually converge without any communication other than operations, thus satisfying the Strong Eventual Consistency (SEC) consistency model. Although this result is empirical, it represents a first step towards the complete validation of the correctness of RenamableLogootSplit.

Memory overhead We then compare the evolution of the size of the data structure. Results are depicted in Figure 6 where the blue line corresponds to the size of the content while the dash-dotted red one exhibits the growth of the LogootSplit data structure.

The dotted green line illustrates the growth of the RenamableLogootSplit document in its best-case scenario where rename operations become stable as soon as they are issued. Former states can then be garbage collected safely, maximising the benefits of the renaming mechanism. In this case, we observe that rename operations reset the overhead of the data structure and eventually reduce by hundred times the document size compared to LogootSplit.

The dashed orange line represents RenamableLogootSplit worst-case scenario. Here, we assume that rename operations never become causally stable and that nodes have to store former states forever. However, obtained results show that RenamableLogootSplit still outperforms LogootSplit and reduces by 66% the overhead. This outcome is due to the change of data structure used to represent the state that takes place when applying a rename operation. To perform updates efficiently, our implementation uses an AVL, a self-balancing tree, to represent the sequence. However, we no longer update the former state once it has been renamed but only query it to transform concurrent operations. We thus store it as an array, a more efficient memory-wise data structure, to save space.

Integration times of standard operations We also measure the impact of the renaming mechanism on the integration times of insert and remove operations.

Figure 7a displays the integration times of local operations while Figure 7b exhibits remote ones. In both cases, the light orange boxplots correspond to integration times of LogootSplit while dark blue ones to the integration times of RenamableLogootSplit. The results show that the renaming mechanism allows to reduce the integration times of future operations.

In Figure 7b, the white boxplots display the integration times of concurrent operations to a rename one. As illustrated in subsection 3.3, these operations require to be transformed before being applied to the renamed state. The results presented here show that the whole process is actually faster than applying them directly on the former state.

Integration time of rename operation Finally, we measure the integration times of rename operations according to the size of the document. Results are displayed in Figure 8 where the blue line corresponds to the integration times of local rename operations while the dashed orange one corresponds to the integration times of remote ones.

The main result of this benchmark is that the unit of time used when applying rename operations is in hundreds of milliseconds. It is necessary to take this into account when designing the strategy used to trigger rename operations in order to minimise the impact of integration times on the user experience.
catch-up protocol to handle concurrent updates. Since consensus algorithms are costly in large-scale distributed systems with churn, Letia et al. [16] introduce a two-tier architecture. Nodes are splitted between the core, a set of stable and highly connected nodes, and the nebula made of the remaining ones. Only members of the core participate in the consensus leading to the renaming.

While quite similar, our approach differs on several aspects. First, in the core-nebula approach, nodes from the core are unable to integrate concurrent operations to the rename one. Nodes from the nebula have to use the catch-up protocol to transform their concurrent operations and to re-broadcast them. It requires additional communications and introduces some delay in the collaboration. In our approach, every node is able to transform and to integrate operations from past epochs directly.

Second, we designed RenamableLogootSplit with fully distributed systems in mind. Nodes can issue rename operations without coordination and use operational transformation to resolve conflicts. However, to simplify the system, it is possible to adopt the core-nebula approach to prevent nodes from issuing concurrent rename operations.

5.2 The LSEQ approach
In [4, 18], Nédelec et al. introduce another approach to address the identifiers growth issue: LSEQ. Its insight consists in combining several strategies to generate new identifiers. It enables LSEQ to reduce the growth of identifiers from a linear progression to a polylogarithmic one.

However, LSEQ does not prevent each inserted element to introduce its own overhead. The document continues to inflate with each insertion. On the other hand, our approach allows the metadata of the data structure to be periodically reset, regardless of the number of elements.

As with the core-nebula approach, it is possible to combine the LSEQ approach with ours. The identifier allocation strategies of LSEQ would allow to reduce the growth of identifiers between rename operations. It would enable to reduce the frequency of the expensive rename operation without deteriorating the performance of the data structure.
6 Conclusions and future work

In this paper, we introduced a novel Sequence CRDT belonging to the variable-size identifiers approach: RenamableLogootSplit. This new data structure embeds a renaming mechanism in its specification. It enables nodes to reassign shorter identifiers to elements and group them into one block to minimise the metadata. Experiments results provided an empirical validation of the correctness of RenamableLogootSplit and showed that it reduces the overhead of the data structure in both best-case (by hundreds times) and worst-case scenarios.

Regarding future work, we would like to present a formal proof of the correctness of RenamableLogootSplit. Another research trail would be to investigate how OT techniques can be integrated within CRDTs to design more complex data types.

Additionally, we now have to design an efficient strategy used to trigger rename operations while minimising their impact on the user experience. User behaviour studies, inspired by [19, 20], could be led in the context of real-time collaborative writing to set an acceptable upper-bound to their integration times.

Finally, we designed RenamableLogootSplit with fully distributed systems in mind. However, for the sake of brevity, we presented it in this paper under the assumption that no concurrent rename operations were issued. This scenario is actually akin to systems in which nodes synchronise to trigger the renaming mechanism. In a future work, we will introduce and evaluate the additional steps required to use RenamableLogootSplit in its original settings.

References


