Department of Informatics, University of Zürich

BSc Vertiefungsarbeit

Detecting Volatile Index Nodes in a Hierarchical Database System

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1 Introduction

Frequently adding and removing data from hierarchical indexes causes them to repeatedly grow and shrink. A single insertion or deletion can trigger a sequence of structural index modifications (node insertions/deletions) in a hierarchical index. Skewed and update-heavy workloads trigger repeated structural index updates over a small subset of nodes to the index. Informally, a frequently added or removed node is called *volatile*. Volatile nodes deteriorate index update performance due to two reasons. First, frequent structural index modifications are expensive since they require many disk accesses. Second, frequent structural index modifications also increase the likelihood of conflicting index updates by concurrent transactions. Conflicting index updates further deteriorate update performance since transactions need to be synchronized in order to resolve the conflict.

Wellenzohn et al. [4] propose the Workload-Aware Property Index (WAPI). The WAPI exploits the workloads' skewness by identifying and not removing volatile nodes from the index, thus significantly reducing the number of expensive structural index modifications. As a result the likelihood of conflicting index updates by concurrent transactions is reduced.

The goal of this project is to implement a WAPI, as proposed by [4] in Apache Jackrabbit Oak in order to improve the transactional throughput of Jackrabbit Oak.

TODO: outline structure of vertiefungsarbeit

1.1 System Architecture

Apache Jackrabbit Oak[1] (Oak) is a hierarchical distributed database system which makes use of a hierarchical index. Multiple transactions can work concurrently by making use of Multiversion Concurrency Control (MVCC) [3], a commonly used optimistic concurrency control technique [2].

Figure 1 depicts Oak's multi-tier architecture. Oak embodies the *Database Tier*. Whilst Oak is responsible for handling the database logic, it stores the actual data on MongoDB[2], labeled as *Persistance Tier*. On the other end, applications can make use of Oak as shown in Figure 1 under *Application Tier*. One such application is Adobe's enterprise content management system (CMS), the Adobe Experience Manager[3].

2 Workload Aware Property Index

The general idea behind the WAPI is to take into account if an index node is volatile before performing structural index modifications. If a node is considered volatile, we prevent removing it from the index.

[1]https://jackrabbit.apache.org/oak/
[2]https://www.mongodb.com/what-is-mongodb
[3]http://www.adobe.com/marketing-cloud/experience-manager.html

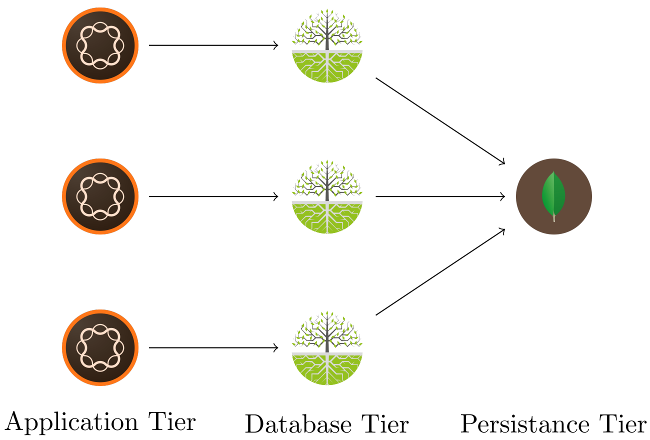


Figure 1: Apache Jackrabbit Oak's system architecture.

In the following section, we will see how to add, query and remove nodes from the index.

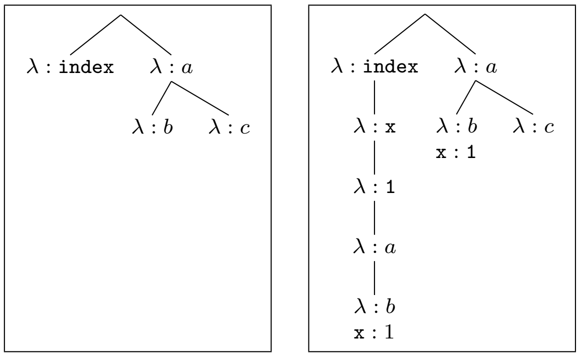
2.1 Insertion

The WAPI is hierarchically organized under `/index` node. The second index level consists of all properties k we want to index. The third index level contains any values v of property k. The remaining index levels replicate all nodes from the root node to any content node with k set to v. Some node m is added to the WAPI iff m has a property k set to v.

The WAPI is updated as described in Algorithm 1. Starting from `/index`, we descend down to `/index/k`, `/index/k/v`. Next, we descend down from `/index/k/v` with a replica from content node m's absolute path from root. While we descend the WAPI, we create any node n that does not exist and assign it to *tail*. Finally, we set *tail*'s property k to v. *tail* corresponds to `/index/k/v/m`.

Example 1. Consider Figure 2. Given snapshot G^i, transaction T_j adds the property $x = 1$ to `/a/b` and commits snapshot G^j. Starting from `/index` and descending down to `/index/x/1/a/b`, we create each node on the way since they do not exist yet. Finally, we set property $x = 1$ on `/index/x/1/a/b`.

$$G^i \xrightarrow{T_j} G^j$$



Snapshot G^i Snapshot G^j

Algorithm 1: AddTripleWAPI

Data: Triple (k, v, m), where k is a property, v a value and m a content node.

tail ⟵ `/index`
for $n \in \langle$ `/i/k`, `/i/k/v`, …, `/i/k/v/m` $\rangle$ **do**
  if n *does not exist* **then**
    create node n
  tail ⟵ n
tail$[k]$ ⟵ v

Figure 2: Adding a node in WAPI. `/i` is an abbreviation for `/index`.

2.2 Querying

Oak mostly executes content-and-structure (CAS) queries [1].

Definition 1. (CAS-Query): Given node m, property k and value v, a CAS query $Q(k, v, m)$ returns all descendants of m which have k set to v, i.e

$$Q(k, v, m) = \{\ n \mid n[k] = v \land n \in desc(m)\ \}$$

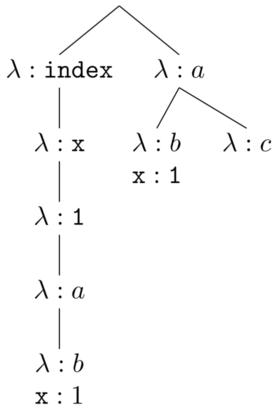
Algorithm 2 describes how we answer the query using the WAPI. Given property k, value v and node m, we start descending down to node `/index/k/v/m`. Next, we iterate through all its descendants n. We return a set consisting of *content* nodes $*n$ corresponding to every *index* node n with property k set to v. If `/index/k/v/m` does not exist, then $desc($`/index/k/v/m`$) = \emptyset$.

Example 2. Consider $Q(x, 1,$ `/a`$)$, every descendant of `/a` with `x` set to 1. Assuming we execute the query on the tree depicted in Figure 3, we receive a set including node `/a/b`, i.e $Q(x, 1,$ `/a`$) = \{$ `/a/b` $\}$

2.3 Deletion

During deletion, we intend to remove a node from the WAPI. Volatile nodes influence the logic of the deletion process. A workload aware property index detects which nodes are volatile and does not remove them. The process of classifying a node as volatile, will be explained in more details in Section 3. For the moment we assume that a function $isVolatile(n)$ is given that classifies n either as volatile or as non-volatile.

Algorithm 3 describes the process of removing a node from the workload aware property index. We first descend down to node m, which we intend to remove. We remove property k from m by setting k's value to NIL. If m is (a) a leaf node, and (b) does not have property k and (c) is not volatile, we remove it. If m was removed, we repeat the process on its parent node. The process ends if we propagate up to `/index` or we reach a node that violates at least one of the above three conditions.



Algorithm 2: QueryWAPI

Data: Query $Q(k, v, m)$, where k is a property, v a value and m a node.
Result: A set of nodes satisfying $Q(k, v, m)$

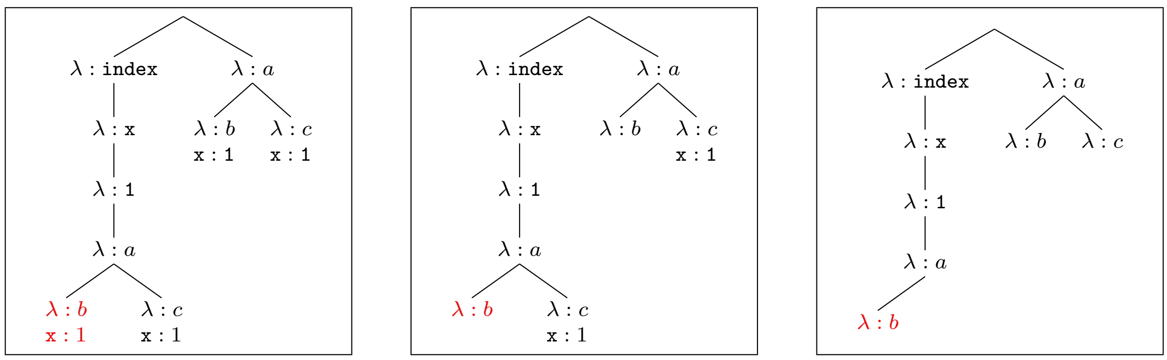
$r \longleftarrow \emptyset$
for $n \in desc($/index/k/v/m$)$ **do**
  if $n[k] = v$ **then**
    $r \longleftarrow r \cup \{*n\}$
return r

Where $desc($`/index/k/v/m`$)$ is the set of descendants of node `/index/k/v/m`, $n[k]$ is property k of node n and $*n$ is the content node corresponding to n.

Figure 3: CAS Query example.

Example 3. Figure 4 depicts the following scenario. Assume `/index/x/1/a/b` (colored red) is volatile in all three snapshots G^i, G^j, G^k. Given snapshot G^i, transaction T_j removes property $x = 1$ from `/a/b` and commits snapshot G^j. Since `/index/x/1/a/b` is volatile, it was not removed from the WAPI, only its property $x = 1$ is removed. Given snapshot G^j, transaction T_k removes property `x` from `/a/c` and commits snapshot G^k. Since `/index/x/1/a/c` is not volatile, it was removed from the WAPI. Since its parent node has another child node, the parent is not removed.

$$G^i \xrightarrow{T_j} G^j \xrightarrow{T_k} G^k$$



Snapshot G^i Snapshot G^j Snapshot G^k

Figure 4: Removing a node from the WAPI. Assume `/index/x/1/a/b` (colored red) is volatile in all three snapshots G^i, G^j, G^k.

Algorithm 3: RemoveTripleWAPI

Data: Triple (k, v, m), where k is a property, v a value and m a node.
$n \longleftarrow$ `/index/k/v/m`
$n[k] \longleftarrow$ NIL
while $n \neq$ `/index` $\wedge\, chd(n) = \emptyset \wedge n[k] \neq v \wedge \neg\, isVolatile(n)$ **do**
    $u \longleftarrow n$
    $n \longleftarrow par(n)$
    remove node u

3 Volatility

Volatility is the measure which is used by the WAPI in order to distinguish when to remove a node or not from the index.

Wellenzohn et al. [4] propose to look at the recent transactional workload to check whether a node n is volatile. The workload on Oak instance O_i is represented by a sequence $H_i = \langle \ldots, G^a, G^b, G^c \rangle$ of snapshots, called a history. Let t_n be the current time and $t(G^b)$ be the point in time snapshot G^b was committed, $N(G^a)$ is the set of nodes which are members of snapshot G^a. $pre(G^b)$ is the predecessor of snapshot G^b in H_i.

Node n is volatile iff n's volatility count is at least τ, called volatility threshold. The volatility count of n is defined as the number of times n was added or removed from snapshots in history H_i over a sliding window of length L.

Definition 2. (Volatility Count): The volatility count of node n is the number of times node n was added or removed from snapshots contained in a sliding window with length L over history H_i.

$$\begin{aligned} vol(n) = |\{G^b | G^b \in H_i \wedge t(G^b) \in [t_{n-L+1}, t_n] \wedge \exists G^a [\\ G^a = pre(G^b) \wedge ([n^a \notin N(G^a) \wedge n^b \in N(G^b)] \vee \\ [n^a \in N(G^a) \wedge n^b \notin N(G^b)])]\}| \end{aligned} \tag{1}$$

Definition 3. (Volatile Node): Node n is volatile iff n's volatility count (Definition 2) is greater or equal than the volatility threshold τ, i.e

$$isVolatile(n) \iff vol(n) \geq \tau$$

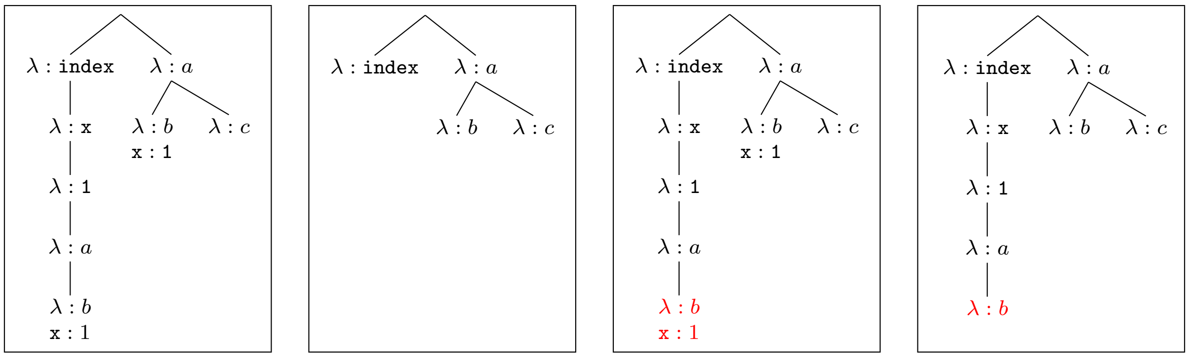
Example 4. Consider the snapshots depicted in Figure 5. Assume $H_h = \langle G^i, G^j, G^k, G^l \rangle$. O_h executes transactions T_j, T_k, T_l. Snapshot G^i was committed at time $t(G^i) = t$. Given snapshot G^i, transaction T_j removes property x from `/a/b` and commits snapshot G^j at time $t(G^j) = t + 1$. Next, transaction T_k adds the property $x = 1$ to `/a/b` given snapshot G^j and commits snapshot G^k at time $t(G^k) = t + 2$. Finally transaction T_l removes property `x` from `/a/b` given G^k and commits G^l at time $t(G^l) = t + 3$.

If $\tau = 2$ (volatility threshold), $L = 4$ (sliding window length) and $n =$ `/index/x/1/a/b`, then:

- at time $t_n = t$ we have that: $vol(n) = 0 \implies isVolatile(n) = \bot$
- at time $t_n = t + 1$ we have that: $vol(n) = 1 \implies isVolatile(n) = \bot$
- at time $t_n = t + 2$ we have that: $vol(n) = 2 \implies isVolatile(n) = \top$
- at time $t_n = t + 3$ we have that: $vol(n) = 3 \implies isVolatile(n) = \top$

Since n is not volatile at $t_n = t$, transaction T_j removes it from the index. But at $t_n = t + 2$, n is volatile (colored red) and transaction T_l does not remove it.

$$G^i \xrightarrow{T_j} G^j \xrightarrow{T_k} G^k \xrightarrow{T_l} G^l$$



Snapshot G^i $t(G^i) = t$ | Snapshot G^j $t(G^j) = t + 1$ | Snapshot G^k $t(G^k) = t + 2$ | Snapshot G^l $t(G^l) = t + 3$

Figure 5: Node `/index/x/1/a/b` becomes volatile after a deletion by T_j and insertion by T_k. Therefore the node cannot be deleted by transaction T_l.

4 Implementation

4.1 Checking Node Volatility

In order to classify a node n as volatile, we have to compute n's volatility count using the corresponding JSON[4] document on MongoDB. The document contains all *revisions* (i.e, versions) of n throughout history H_i of an Oak instance O_i. Figure 6 depicts such a document. We omitted non relevant properties. Property `"_deleted"` contains key value pairs which encode when the node was added or removed from snapshots. A key is a revisions that is composed of three parts connected by a dash (-): (1) a timestamp, (2) a counter that is used to differentiate between value changes at the same instance of time, and (3) the identifier i of the Oak instance O_i committing the change.

[4]http://www.ecma-international.org/publications/files/ECMA-ST/ECMA-404.pdf

Example 5. Consider `r15cac0dbb00-0-2` in Figure 6. `r` is a standard prefix and can be neglected. The `15cac0dbb00` following `r`, is a timestamp (number of milliseconds since the Epoch) in hexadecimal encoding which represents the time at which the change was committed. The `0` following the timestamp, is a counter which is used for tie-breaking between transactions committed at the same instance of time. The `2` following the counter, tells that the change was committed by the Oak instance O_2 with an id of `2`.

```
{
    "_id": "5:/index/x/1/a/b",
    "_deleted": {
        "r15cac0dbb00-0-2": false,
        "r15cabff1500-0-2": true,
        "r15ca9f191c0-0-1": false,
        /* ... */
    },
    /* ... */
}
```

Figure 6: JSON document of an index node.

Having seen what a node document looks like, we can now describe how we classify a node as volatile. Figure 7 shows the native implementation of $isVolatile(n)$ in Java. $isVolatile(n)$ is given a node's corresponding document. We iterate through the revisions of property `"_deleted"` in most-recent first fashion. Notice that the `keySet` referred to in the Java code is, in Java's terminology, an ordered set. If a revision is outside the sliding window we stop iterating because remaining revisions cannot be more recent. We increment the volatility count for every visible revision. A revision is visible if it is contained in the Oak instance's history. If the volatility count reaches at least τ we break the loop. When exiting the loop, we finally check if the volatility count is at least τ and return the result.

4.2 Document Splitting

Jackrabbit Oak periodically checks a node's corresponding documents for their size and if necessary splits them up and moves old data to a new split document. In order to avoid round-trips while computing the volatility count, we modify the document split implementation as mentioned in [4]. We essentially leave at most τ revisions in the document and move all other revisions to a new split document. Since Oak has to operate in a distributed environment, we only move revisions committed by the local instance in order to prevent race conditions.

Figure 8 depicts the Java implementation of the document splitting process. We iterate through the revisions of the `"_deleted"` property of the given document in most-recent first fashion. A revision gets moved to the split document iff: (1) it is visible, (2) is not in the sliding window or at least τ revisions already exist in the document and (3) the revision was committed by the local Oak instance, i.e, $visible(r) \wedge [t(r) \notin [t_{n-L+1}, t_n] \vee vol \geq \tau] \wedge c(r) = O_i \iff moveToSplitDocument(r)$.

```java
/**
 * Determines if node is volatile.
 * @param nodeDocument: document of node.
 * @returns true iff node is volatile.
 */
boolean isVolatile(NodeDocument nodeDocument) {

    int vol = 0;

    for (Revision r : nodeDocument.getLocalDeleted().keySet()) {
        if (!isInSlidingWindow(r)){
            break;
        }
        if (!isVisible(r)){
            continue;
        }
        if (vol++ >= getVolatilityThreshold()) {
            break;
        }
    }
    return vol >= getVolatilityThreshold();
}
```

Figure 7: Java implementation for detecting volatile index nodes.

Example 6. Consider Figure 9. We see how a node's corresponding document is split, assuming $\tau = 3$, $O_i = 1$, $t_{\texttt{last\_sync}} = 2017.06.15\ 13{:}59$, $L = 24$ hours, $t_n = 2017.06.15\ 14{:}01$. Figure 10 shows a table with intermediate values during computation. "$t(r)$" is the point of time revision r was committed. Only the day, hours and minutes are showed for brevity. "$c(r)$" is the cluster node which committed revision r. "Vis." is true iff the revision is visible to the local cluster node. "∈Win." is true iff the revision is in the sliding window. "Vol." represents the volatility count at that step of the iteration. "Split" is true iff the revision is moved to the split document.

We will briefly walk you through the iteration during the document split depicted in Figure 9. r_1 does not increment the volatility count, since it is not visible to the local Oak instance. Thus r_1 is not moved to the split document. The three next revisions, r_2, r_3, r_4, increment volatility because they are in the sliding window but are not moved to the split document because $vol < \tau$. r_5 is still in the sliding window and therefore increments volatility. Since there are already τ revisions in the document, we move r_5 to the split document. Finally, any following revisions committed by the local Oak instance (r_7, r_8, r_9) are moved to the split document since there are τ revisions in the document.

```java
/**
* Splits the "_deleted" property on the given document.
* @param NodeDocument the node document.
*/
void splitDeleted(NodeDocument nodeDocument) {

    int vol = 0;

    for (Revision r : nodeDocument.getLocalDeleted().keySet()){
        if (!isVisible(r)){
            continue;
        }
        if (isInSlidingWindow(r) && vol++ < getVolatilityThreshold()){
            continue;
        }
        if (r.getClusterId() != getClusterId()) {
            continue;
        }
        moveToSplitDocument(r);
    }
}
```

Figure 8: Java implementation for splitting the node document.

```
{
  "_id": "5:/index/x/1/a/b",
  "_deleted": {                  /* DD HH:MM */
    "r15cac0dbb00-0-2": false,   /* 15 14:00 */
    "r15cabff1500-0-2": true,    /* 15 13:44 */
    "r15ca9f191c0-0-1": false,   /* 15 04:10 */
    "r15ca76fc8e0-0-1": true,    /* 14 16:29 */
    "r15ca73b9980-0-1": false,   /* 14 15:32 */
    "r15ca5e9c520-0-2": true,    /* 14 09:23 */
    "r15ca5a8c480-0-1": false,   /* 14 08:12 */
    "r15ca5a6efc0-0-1": true,    /* 14 08:10 */
    "r15ca58e37a0-0-1": false    /* 14 07:43 */
  },
  /* ... */
}
```

(a) Before splitting.

```
{
  "_id": "5:/index/x/1/a/b",
  "_deleted": {                  /* DD HH:MM */
    "r15cac0dbb00-0-2": false,   /* 15 14:00 */
    "r15cabff1500-0-2": true,    /* 15 13:44 */
    "r15ca9f191c0-0-1": false,   /* 15 04:10 */
    "r15ca76fc8e0-0-1": true,    /* 14 16:29 */
    "r15ca5e9c520-0-2": true     /* 14 09:23 */
  },
  /* ... */
},
{
  "_id": "6:/index/x/1/a/b/r15ca58e37a0-0-1",
  "_deleted": {                  /* DD HH:MM */
    "r15ca73b9980-0-1": false,   /* 14 15:32 */
    "r15ca5a8c480-0-1": false,   /* 14 08:12 */
    "r15ca5a6efc0-0-1": true,    /* 14 08:10 */
    "r15ca58e37a0-0-1": false    /* 14 07:43 */
  },
  /* ... */
}
```

(b) After splitting.

Figure 9: Document splitting. We use the same parameters as in Example 6.

r	$t(r)$	$c(r)$	Vis.	$\in$Win.	Vol.	Split
r_1	15 14:00	2	$\bot$	$\top$	0	$\bot$
r_2	15 13:44	2	$\top$	$\top$	1	$\bot$
r_3	15 04:10	1	$\top$	$\top$	2	$\bot$
r_4	14 16:29	1	$\top$	$\top$	3	$\bot$
r_5	14 15:32	1	$\top$	$\top$	4	$\top$
r_6	14 09:23	2	$\top$	$\bot$	4	$\bot$
r_7	14 08:12	1	$\top$	$\bot$	4	$\top$
r_8	14 08:10	1	$\top$	$\bot$	4	$\top$
r_9	14 07:43	1	$\top$	$\bot$	4	$\top$

Figure 10: Intermediate values of computation while splitting document `/index/x/1/a/b` as shown in Figure 9. We use the same parameters as in Example 6.

References

[1] C. Mathis, T. Härder, K. Schmidt, and S. Bächle. XML indexing and storage: fulfilling the wish list. *Computer Science - R&D*, 30(1):51–68, 2015.

[2] M. T. Özsu and P. Valduriez. *Principles of Distributed Database Systems, Third Edition*. Springer, 2011.

[3] G. Weikum and G. Vossen. *Transactional Information Systems: Theory, Algorithms, and the Practice of Concurrency Control and Recovery*. Morgan Kaufmann, 2002.

[4] K. Wellenzohn, M. Böhlen, S. Helmer, M. Reutegger, and S. Sakr. A Workload-Aware Index for Tree-Structured Data. To be published.

5 Appendix

5.1 Helper Functions

Figure 11 presents the Java implementation of two helper functions. $isVisible(r)$ determines if revision r is visible to the local Oak instance O_i. As mentioned in [4], r is visible to O_i iff it is contained in a snapshot in history H_i. $isInSlidingWindow(r)$ determines if revision r is in the siliding window.

```java
/**
 * Checks if r is visible to the local cluster node
 * @param r the revision
 * @returns true iff r is visible to the local cluster node
 */
boolean isVisible(Revision r) {
    return r.getClusterId() == getClusterId()
            || (r.compareRevisionTime(documentNodeStore
                    .getHeadRevision()
                    .getRevision(getClusterId())) < 0);
}

/**
 * Checks if r is in the sliding window
 * @param r the revision
 * @returns true iff r is in the sliding window
 */
boolean isInSlidingWindow(Revision r){
    return System.currentTimeMillis() - getSlidingWindowLength() < r.getTimestamp();
}
```

Figure 11: Java implementation for helper functions.