XPath-based Concurrency Control for XML Data

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Abstract For concurrency control of XML data, this paper proposes a new locking method based on XPath with a new data management model. Although increasing concurrency for XML data becomes an important issue in XML data management, few effective methods providing high concurrency of transactions working on the same XML document have been proposed so far. To overcome this problem, we propose a locking method that can achieve high concurrency while guaranteeing the serializability of transactions to the same XML document. In the proposed method, logical locks are set on XPath expressions used in transaction accesses, and conflicts that violate serializability are detected each time a read or a write access is requested by concurrent transactions. Efficient algorithms for detecting conflicts are also proposed in this paper. Since the proposed locking is at the level of precise data in XML documents, high concurrency for XML data can be achieved assuring serializability.

Key words Concurrency control, XML data management, XPath, Locking, Serializability, Phantom problem

1. Introduction
1.1 Backgrounds

As the eXtensible Markup Language (XML) [2] becomes a widely adopted standard for data representation in various application areas, the number of XML documents is rapidly growing and the subsequent need for sharing XML documents by different applications and multiple users is increasing. Concurrency control of transactions working on the same document is thus an important issue in XML data management. Serializability, which requires that concurrent transactions must produce the same result as the same transactions executed in a certain sequential order, has been considered as a fundamental problem for concurrency control, and locking is known as a robust technique to handle this problem. Locking to ensure the serializability has been extensively investigated for traditional RDBMSs, but not yet for XML data management systems. In the present XML data management, XML documents are usually stored either to relational databases as BLOBs or to native XML databases as XML format. However, in both cases, locking is often at the level of entire documents and thus no concurrency of transactions to the same documents is actually provided [1]. The aim of this paper is to overcome this problem and to achieve high concurrency for XML documents while ensuring serializability.

In order to ensure the serializability of transactions, locking must prevent the phantom problem [5]. A phantom indicates the data that was already disappeared from or will appear to a database, and thus locking on such phantoms is difficult since the phantoms do not physically exist at the time of locking. To solve the phantom problem, two well-known forms of locking have been proposed so far: physical index-based locking and logical predicate-based locking.

The index-based locking, such as key range locking [9], prevents the phantom problem by locking on the index entry to the phantom. So far, because of low locking cost and useful index structure such as the B-Tree [7], the index-based locking have been widely adopted for RDBMSs. However, the index-based locking is not applicable for XML data management in the absence of an efficient index structure for an XML document model.

The predicate-based locking, such as predicate locking [5] and precision locking [8], prevents the phantom problem by locking on the predicate that identifies the phantom. In the predicate locking, any conflict to violate serializability is detected by checking if two predicates used in concurrent transaction accesses are mutually satisfiable. The predicate locking is more general than the index-based locking, but is more expensive since such the satisfiability problem between arbitrary two predicates is known to be NP-complete. To overcome this shortcoming, the precision locking performs the conflict check between predicates and updates, instead of that between two predicates, in the following way: As a transaction performs a read access and a write access, the predicate used in the read access and the update by the write access are posted in a predicate list and an update list, respectively. In order to detect a conflict between predicates and updates by different transactions, each predicate (update) posted is checked against updates (predicates) by other transactions in the update list (the predicate list). The precision locking performs the conflict check against only actual predicates and updates, and thus provides high concurrency and a relatively lower cost than the predicate locking. Inherently, we conjecture that the concept of the precision locking could be helpful to ensure serializability in XML data management. However, the problem to perform practical conflict checks that can handle XML documents still remains.

1.2 New Results

Our contribution is a new locking method that guarantees serializability and provides high concurrency of transactions to the same XML documents. To our best knowledge, the only one method by Grabs et al. [6] tackled the same concurrency control problem for XML documents so far. They proposed a combination of well-known granularity locking and predicate locking which provides high concurrency, but their locking is applicable to only restricted XML documents with simple XPath query for transaction accesses. Against [6], our method allows general XML documents and full XPath query. In the proposed method, each time an access is requested, conflict checks to ensure serializability are performed in the following way: As for each read access, conflicts against all
previous write accesses by distinct transactions are checked. As for
each write access, conflicts against all previous read accesses by dis-
tinct transactions are checked. In the following, the former is called
a read-write check; the latter is called a write-read check.

The basic ideas of the proposed method are as follows. First, we
introduce a new data management model, which handles the three
kinds of documents: (1) an original document in the database, de-
noted by $D_{or}$, (2) a copy of $D_{or}$ for each transaction $T_i$, denoted by
$D_i$ and (3) a copy of $D_{or}$ for detecting conflicts, denoted by $D_{all}$. 
Each transaction $T_i$ has accesses to document $D_i$ instead of or-
iginal document $D_{or}$, and write accesses by $T_i$ update both $D_i$ and
$D_{all}$. Document $D_{all}$ thus represents the document state updated
by all transactions. Only when $T_i$ commits, the updates by $T_i$ are
reflected in $D_{or}$.

Next, we propose a logical locking approach in which locks are
set on the XPath expressions used read accesses and conflicts be-
tween the XPath expressions and the updates by write accesses are
checked. To detect conflicts, checking the satisfiability of an update
with an XPath expression is necessary but is difficult since XPath
is a path-based and semistructured query language, not a generic
boolean predicate. In order to handle this deficiency, we present
a sufficient condition such that any conflict between the XPath ex-
pression and the update can be detected by checking the condition
when evaluating the expression on two documents such that one
contains the update and the other does not. The proposed locking
thus resolves the phantom problem by regarding XPath expressions
as predicates.

Based on our data management model and XPath-based locking,
conflicts between concurrent transaction accesses are checked as
follows: The read-write check is performed by comparing nodes in
documents $D_i$ and $D_{all}$ which are reachable when evaluating XPath
expressions. Since the updates of all previous write accesses are re-
lected in $D_{all}$, the read-write check can be completed by just one
comparison using $D_{all}$. On the other hand, dealing with the read
access is typically complicated much more than dealing with the
read access. The write-read check is performed based on the idea
of using previous states of $D_{all}$. We also present an algorithm to
dynamically determine whether the current state of $D_{all}$ provides a
large effect on subsequent write-read checks. In addition, we show
that the proposed scheduling of saving previous states of $D_{all}$ is
always optimal in terms of the effects obtained.

2. Preliminaries

This section describes the XML document model and the trans-
action access model used in our research.

2.1 XML Document Model

An XML document is modeled as a tree, which details the parent-
child relationship between various elements of the document. Each
node in the tree has a type such as element, text and attribute. (For
more detail of XML, refer to [2].) In the following, an XML docu-
ment is referred to as a document for short. Fig. 1 and Fig. 2 re-
spectively show an example XML document and its representation as a
tree. In Fig. 2, “e”, “t” and “a” attached to each node represent that
the node type is element, text and attribute, respectively.

2.2 Transaction Model

We consider a set of concurrent transactions $T = \{T_1, \ldots, T_n\}$
$(n \geq 2)$ which accesses the same document where $n$ denotes the
number of transactions. Hereafter, the term transactions means con-
current active transactions otherwise indicated. In this paper, the
case where a transaction accesses to more than one document is not
considered since such accesses could be classified into the accesses
to each document and only accesses to the same document is impor-
tant when considering concurrency control.

Each transaction sequentially performs several read accesses ($R$-
accesses, for short) and write accesses ($W$-accesses, for short) to
the document. The time-ordered sequence of the accesses by transac-
tion $T_i$ is referred to as an access sequence of $T_i$ and is denoted by
$AS_i$. The access sequence of $T_i$ then consists of read sequences ($R$-
sequences, for short) and write sequences ($W$-sequences, for short),
and is modeled as illustrated in Fig. 4. An read sequence (write
sequence) indicates a sequence of consecutive read accesses (write
accesses) in the access sequence. We also define the following no-
tations:

- $W S_i(k)$ ($k > 0$) : the k-th write sequence of $T_i$.
- $|W S_i(k)|$ : the number of write accesses in $W S_i(k)$.
- $\omega_i$ : the current number of write sequences of $T_i$.
- $R S_i(k)$ ($k \geq 0$) : if $k = 0$, the first read sequence; oth-
erwise, the read sequence right after write sequence $W S_i(k)$.

Fig. 4 shows an example access sequence of a transaction $T_i$.
In the figure, the box and the vertical line represent a write access
and a read sequence which contains one or more read accesses, re-
spectively. Write sequences $W S_i(1)$ and $W S_i(2)$ are the first and
the second write sequences respectively, and $|W S_i(1)| = 1$ and
$|W S_i(2)| = 2$. Read sequence $R S_i(0)$ denotes the read sequence
before the first write access, and read sequences $R S_i(1)$ and $R S_i(2)$
follow right after $W S_i(1)$ and $W S_i(2)$, respectively.

2.3 XPath Access Model

We assume that transactions have accesses to the document using
the XPath [4], which is the language to address parts of the XML
document and is being used as a base in a number of other XML
standards such as XQuery [3]. We assume that the reader is famil-
ilar with XPath and basic notations such as an XPath expression, a
location path, and an axis. (For the detail of XPath, refer to [4].)

An R-access is performed to the document by specifying an
XPath expression that identifies a node (or nodes) in the document.
A read operation is represented by Read(path) with XPath expres-
3. Proposed Locking Method

In order to ensure the serializability, a locking method must prevent any conflict between R-accesses and W-accesses executed concurrently by different transactions. The proposed locking method detects conflicts between XPath expressions used in R-accesses and updates by W-accesses by different transactions under our data management model. This section describes a new data management model and the overview of conflict check.

3.1 Data Management Model

The data management model is illustrated in Fig. 5 where each triangle represents a document state and the following three kinds of document states are contained:

- \(D_{st} \): the committed document state in the database.
- \(D_i \): for \(T_i \), the document state containing the updates of \(T_i \).
- \(D_{all} \): the document state containing the updates of all active transactions.

The state of \(D_{st} \) is copied to \(D_{all} \) initially, and as a new transaction \(T_i \) is issued, documents \(D_{st}, D_i \) and \(D_{all} \) are handled and updated in the following manner:

1. When \(T_i \) starts, generate \(D_i \) as a copy of \(D_{st} \).
2. While \(T_i \) proceeds, \(T_i \) accesses to \(D_i \) instead of \(D_{st} \). When \(D_i \) is updated by each W-access of \(T_i \), the update is also reflected in \(D_{all} \).
3. When \(T_i \) commits, reflect the updates by \(T_i \) in \(D_{st} \).
4. When \(T_i \) aborts, \(D_i \) is just deleted and \(D_{all} \) is regenerated.

Fig. 4 An access sequence of transaction \(T_i \).

A W-access is performed to the document by specifying a write operation and the target node (or nodes) of the write operation. The target node is selected by the R-access to the document. We consider three kinds of write operations on the document: insert, delete, and replace. The insert operation and the delete operation could be to insert and delete a node (or nodes) in the document. The replace operation could be to replace the value of a node, such as an element node or an attribute node, with a new value. Note that the proposed locking does not depend on the type of write operation.

[Example 1] Consider the document shown in Fig. 2. First, suppose that an R-access \(Read(path) \) with \(path=\text{"flower[name=Rose]/price"} \) is performed to the document. XPath expression \(path \) is evaluated on the document and then element node “price” contained in “flower” element whose “name” element has the value of “Rose” is selected. The selected node is node \(y \) in Fig. 2. The selected node is marked with bold lines in Fig. 2. Note that the value of the selected node is “500”, that is the value of its child text node. Next, suppose that a W-access that replaces the value of the selected node by the R-access to “350” is performed to the document. The document is then updated by the W-access as shown in Fig. 3. The updated parts are marked with bold lines in Fig. 3.

In the proposed locking, each time a transaction requests an R-access or a W-access, checking conflicts of the access against previous accesses by other transactions is performed. Among the four cases shown in Fig. 6, checking the read-write conflict (Case b) and the write-read conflict (Case c) is sufficient to ensure the serializability. There is no conflict between R-accesses. On the other hand, the write-write conflict can be detected by the read-write conflict or the write-read conflict since, before a write operation on some nodes that leads to a conflict, a read operation on the same nodes is performed.

Fig. 5 Data management model.

<table>
<thead>
<tr>
<th>Requested access</th>
<th>Previous access by other transactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Read</td>
<td>Write</td>
</tr>
<tr>
<td>a)</td>
<td>b) (\sqrt{\phantom{a}} )</td>
</tr>
<tr>
<td>c) (\sqrt{\phantom{b}} )</td>
<td>d) (\sqrt{\phantom{a}} )</td>
</tr>
</tbody>
</table>

\(\sqrt{\phantom{a}} \) means that the detection of a conflict is needed.
with previous R-accesses of other transactions.

When a conflict is detected by the R-W check or the W-R check, a requested access is delayed until the other transaction that the access conflicts finishes. Actually which transaction is blocked can be determined by transaction priority. Deadlock which occurs by blocking transactions could be detected by using well-known solutions such as the wait-for graph [7]. The proposed algorithms for the R-W check and the W-R check are given in Section 4 and Section 5, respectively.

4. Read-Write Check

This section describes the proposed method for the R-W check. Each time an R-access is requested, the R-W check is performed for detecting the R-W conflict caused by the R-access. The R-W conflict is detected based on the XPath evaluation under our data management model. An conflict of an R-access with previous W-accesses means that the result of the R-access to a document is different from that to the document updated by the W-accesses. Hereafter we define the boolean function Conf(R, W) to be true (1) iff an R-access R conflicts a sequence, W, of W-accesses.

Consider that a transaction Ti requests an R-access Ri = Read(path). In our data management, Ri is then performed to document Dj and some nodes on Dj are selected by evaluating XPath expression path on Dj as a result. In the following, the function GetN(Dj, path) is defined as the nodes on document Dj selected by XPath expression path. Let Wj denote a sequence of previous W-accesses by transaction Tj. Iff Conf(Ri, Wj) = true with Ri = Read(path), then

\[
\text{GetN}(D_j, \text{path}) \neq \text{GetN}(\text{Merge}(D_j, D_j'), \text{path}).
\]  

(4.1)

(Since the previous W-accesses of Tj is reflected in Dj, Merge(Dj, Dj') is equal to the state of Dj updated by Wj.) The conflict of Ri with previous W-accesses by any other transaction Tj is then detected by checking formula (4.1).

Here we note that an R-access could conflict with W-accesses of more than one transactions even when the R-access does not conflict with those of each of the transactions. For transactions Tj and Th in (T - {Ti}), there is a case where Conf(Ri, Wj + Wh) = true but Conf(Ri, Wj) ≠ true and Conf(Ri, Wh) ≠ true. The conflict is then detected by checking if GetN(Dj, Ri) \neq GetN(Dj', Ri) where Dj' is the state of Dj merging both Dj and Dh. On the other hand, there is also a case where Conf(Ri, Wj) = true or Conf(Ri, Wh) = true but Conf(Ri, Wj + Wh) ≠ true. Hence the R-W conflict of Ri with previous W-accesses needs to be checked against all combinations of transactions in (T - {Ti}), but such a conflict check against all the combinations is extremely time consuming. (The number of all combinations to be considered for each R-access is \(2^n - 1 - 1\).

To handle this problem, we present a sufficient condition for the R-W conflict of Ri such that a conflict caused by Ri with previous W-accesses by any set of other transactions is detected by checking if the condition holds in the XPath evaluation on the state of document Dj updated by the W-accesses of all transactions. In other words, if Ri causes a conflict with previous W-accesses by any set of transactions in T - {Ti}, then the condition holds with the state of document Dj updated by Wj + \cdots + Wj + \cdots + Wn(= W).

In the following, we define the function GetD(Dj, W) as the state of document Dj updated by W-accesses W. Let \(N_j\) in GetD(Dj, W) be the part, i.e. nodes, updated by Wj.

\[
\text{For any } N_j \text{ and } N_h (j \neq h), N_j \cap N_h \neq \emptyset \quad (4.2)
\]

since there is no conflict between previous W-accesses \(W_j\) and \(W_h\). (Such the conflict was previously detected.) In addition, for each node in \(N_j\), all nodes in the subtree whose root is the node are also contained in \(N_j\).

In the following explanation for the conflict check, we refer to the semantics of XPath presented in [10], which is shown in Appendix A. The proposed method however is a general approach that can be applicable to any semantics for XPath. To save space, we omit the precise explanation for the semantics of XPath, so refer to [10] for more detail. The semantics of XPath is specified by three functions \(S, Q, \text{and } E\) with two parameters: an axis \(a\) and a context node \(x\). Among the three functions, both functions \(Q\) and \(E\) recursively call function \(S\) and the results of them (boolean and numerical value, respectively) are determined from the nodes returned by \(S\). Here we thus concentrate on function \(S\). Function \(S^a[p]x(D)\) denotes the nodes selected by location path \(p\) with parameters \(a\) and \(x\). When XPath expression \(\text{path}\) is evaluated on document \(D_i\), function \(S\) could be called several times for specifying the resulting nodes on \(D_i\). We use the term \(S^a[p]x(D)\) to indicate the result of \(S\) on \(D_j\). Lemma 1 and Theorem 1 then hold.

[Lemma 1] If GetN(Dj, path) \neq GetN(Dj', path) with XPath expression path and two documents Dj and Dj', function \(S\) such that \(S^a[p]x(D_j) \neq S^a[p]x(D_j')\) is called in the evaluation of path on \(D_j\) and \(D_j'\).

proof: Suppose that such function \(S\) is not called in the evaluation of path, that is, \(S\) always returns the equivalent results for \(D_j\) and \(D_j'\). Then, obviously, GetN(Dj, path) \equiv GetN(Dj', path). This is a contradiction. □

[Theorem 1] Consider two sets, \(T'\) and \(T''\), of transactions such that \(T' \cap T'' = \emptyset\) and \(T' + T'' \subseteq T - \{T_i\}\). Let \(W'\) and \(W''\) be previous W-accesses of \(T'\) and \(T''\), respectively. If \(R_i = \text{Read(path)}\) conflicts with \(W''\), function \(S\) such that

\[
S^a[p]x(D_i) \neq S^a[p]x(\text{GetD}(D_i, W' + W''))
\]

is called in the evaluation of path on \(D_i\) and GetD(Di, W' + W'').

proof: Let \(W = W' + W''\), \(D_i' = \text{GetD}(D_i, W')\), and \(D_i'' = \text{GetD}(D_i, W'')\). By Lemma 1, the theorem holds if GetN(Di, path) \neq GetN(Di', path). Otherwise, GetN(Di, path) \neq GetN(Di', path) and thus function \(S\) such that \(S^a[p]x(D_j) \neq S^a[p]x(D_j')\) is called in the evaluation of path on \(D_j\) and \(D_j'\). Then, there are a node \(y \in S^a[p]x(D_j)\) and a node \(y' \in S^a[p]x(D_j')\) such that \(y \neq y'\). Moreover, by formula (4.2), there is a node \(y'' \in S^a[p]x(D_i)\) such that \(y'' \equiv y'\). Since \(y \neq y''\), \(S^a[p]x(D_i) \neq S^a[p]x(D_i')\).

By Theorem 1, using document \(D_i\) and a document updated by transactions, the conflict between R-access \(R_i\) and previous W-accesses of any subset of transactions can be detected. In our data management, the updates by all previous W-accesses are reflected in \(D_{a(i)}\). Thus, if an R-access \(R_i = \text{Read(path)}\) causes the R-W conflict with previous W-accesses of any set of transactions, the evaluation of path on \(D_i\) and \(D_{a(i)}\) must call a function \(S\) such that

\[
S^a[p]x(D_i) \neq S^a[p]x(D_{a(i)}).
\]

(4.4)

Hence, the R-W conflict of \(R_i\) is detected by checking formula (4.4) when function \(S\) is called for the XPath evaluation. Note that this is a sufficient condition for a conflict, i.e., the calling such function \(S\) whose results are not equivalent does not necessarily lead to a
conflict. A more efficient sufficient condition for the conflict check is omitted here (although we have some idea) but will be addressed in future work. In addition, the equivalence check for function $S$ is reduced in the following way. Consider the case where function $S^\alpha[p]x(D_i)$ recursively calls $S'^{\alpha'}[p'][x'](D_i)$ with $x' \in S$. As mentioned previously, if a node $x'$ in document $D_i$ ($D_{all}$) is updated, nodes in the subtree whose root is $x'$ are also updated. Hence, if axiom $\alpha'$ is for searching nodes in the subtree of context node $x'$ and formula (4.4) holds, then $S'^{\alpha'}[p'][x'](D_i) \not\equiv S'^{\alpha'}[p'][x'(D_{all})]$. Therefore, when function $S$ is recursively called by function $S'$ with such an axis, the equivalence check for $S'$ can be omitted since the conflict can be detected by the equivalence check for $S$.

[Example 2] Consider that $T_i$ requests an R-access $Read(path)$ with path="flower[price<400]/name". Suppose that $D_i$ equals to the document shown in Fig. 2 and $D_{all}$ equals to the document shown in Fig. 3, which was updated by a previous W-access of the other transaction. When path is evaluated on $D_i$ and $D_{all}$, function $S^\alpha[price]x$ with $a = child$ is called. The resulting node, $y$, of $S$ on $D_i$ is not equivalent to that on $D_{all}$, that is, $S^\alpha[price]x(D_i) \not\equiv S^\alpha[price]x(D_{all})$. Therefore, the conflict of the R-access with the W-access is detected.

Here we define the boolean function $Check(D, D', R)$ with two documents $D$ and $D'$ and R-access $R = Read(path)$ as follows: $Check = ok$ (1) if function $S$ is called in the evaluation of path such that the resulting nodes on $D$ are not equivalent to the resulting nodes on $D'$; $Check \neq ok$, otherwise. The following theorem then holds.

[Theorem 2] If an R-access $R_i$ by a transaction $T_i$ leads to the R-W conflict, $Check(D_i, D_{all}, R_i) \neq ok$. \hfill $\Box$

The proposed algorithm for the R-W check is then as follows:

When a transaction $T_i$ requests an R-access $R_i$,

1. Check if $Check(D_i, D_{all}, R_i) = ok$.
2. If it holds, then $R_i$ causes no R-W conflict and $T_i$ proceeds.
3. Otherwise, $R_i$ causes a R-W conflict with other transactions. Find transaction $T_j(i \neq j, 1 \leq j \leq n)$ that causes the conflict with $R_i$, and block $T_i$ until $T_j$ finishes. When $T_j$ finishes, $T_i$ restarts.

In the R-W check, XPath evaluation is processed in both $D_i$ and $D_{all}$. The execution cost needed for the proposed algorithm is then the sum of the cost for evaluating an XPath expression and the cost for equivalence checks in the XPath evaluation. Equivalence checks can be easily implemented by, for instance, sharing a pointer between equivalent nodes in distinct documents.

5. Write-Read Check

This section describes the proposed method for the W-R check. Each time a W-access is requested, the W-R check is performed for detecting the W-R conflict caused by the W-access, using $D_{all}$ under our data management model.

Consider that a transaction $T_i$ requests a W-access $W_i$. In our data management, $W_i$ is performed to document $D_i$, and then $D_i$ is updated by $W_i$ as a result. Let $D'_i = Get(D_i, W_i)$. Let $R_j$ be a previous R-access by any other transaction $T_j$. By Theorem 2, if $W_i$ causes a conflict with $R_j$, then $Check(D'_i, Merge(D'_i, D'_i), R_j) \neq ok$ where $D'_i$ denotes the previous state of $D_i$ to that $R_j$ was performed. When $W_i$ is requested, this conflict check for $W_i$ is needed against each of all previous R-accesses by any transaction $T_j\in T - \{T_i\}$. Thus all the previous states of $D_j$’s for each $T_j$ are needed for the W-R check when $T_i$ requests a W-access.

Two simple ways to obtain the previous states of $D_j$’s are considered: one is storing all the previous states and the other is regenerating the previous states by performing previous updates again. However both of them are impractical if there are a number of concurrent transactions and updates due to memory and time consuming, respectively. To overcome this deficiency, we present the method for an efficient W-R check using previous states of $D_{all}$ instead of using previous states of $D_i$ for every transaction $T_i$.

5.1 Write-Read Check using previous $D_{all}$'s

Consider a W-access $W_i$ requested by $T_i$ and a previous R-access $R_j$ in R-sequence $RS_j(k) (0 \leq k \leq wn_j)$ of $T_j$. (Recall that $wn_j$ is the current number of W-sequences of $T_j$.) Now we define the notation $D_j(k)$ with $(0 \leq k \leq wn_j)$ as follows: if $k = 0$, $D_j(0) = D_{all}$; otherwise, $D_j(k) = Get(D_{all}, W_k)$ where $W = WS_j(1) + \cdots + WS_j(k)$. Then $D_j(k)$ is equivalent to the previous state of $D_j$ to that R-access $R_j$ in $RS_j(k)$ is performed. Hence, a conflict with $R_j$ caused by $W_i$ is detected by checking if

$$Check(D_j(k), Merge(D'_i, D_j(k)), R_j) \neq ok.$$  (5.1)

In the following explanation, we refer to Fig. 7, which illustrates an example of two transactions $T_i$ and $T_j$. Suppose that W-sequence $WS_j(k)$ finished and $D_j$ and $D_{all}$ were updated by the last W-access in $WS_j(k)$ at time $t_i$. Suppose also that the next W-sequence $WS_j(k + 1)$ started right after time $t_2$. Document $D_j(k)$ is then the state of $D_j$ at any time $t$ with $t_i \leq t \leq t_2$. ($D_j(k)$ equals to the state of $D_j$ in which updates until $WS_j(k)$ are reflected.) Let $D'_{all}$ be the state of $D_{all}$ at any time $t(t_i \leq t \leq t_2)$. Document $D'_{all}$ is the document state updated by all transactions by time $t$, that is, $D'_{all}$ is the document merging $D_j(k)$ and all $D_i's(i \neq j, 1 \leq i \leq n)$ at time $t$. By Theorem 2,

$$Check(D_j(k), D'_{all}, R_j) = ok$$  (5.2)

since $R_j$ was checked not to lead to the R-W conflict when it is requested. By formula (5.1) and equation (5.2), we obtain the following theorem.

[Theorem 3] If a W-access $W_i$ by a transaction $T_i$ leads to the W-R conflict, there is an R-access $R_j$ in $RS_j(k)(0 \leq k \leq wn_j)$ by any other transaction $T_j$ such that

$$Check(D'_{all}, Merge(D'_i, D'_{all}), R_j) \neq ok.$$
where $D'_i = GetD(D_i, W_i)$ and $D'_i$ is a previous state of $D_i$ at any time after $WS_j(k)$ and before $WS_j(k + 1)$. 

By Theorem 3, the W-R conflict caused by a requested W-access with any R-accesses in $RS_j(w'_n)$ can be detected by using the previous state of $D_i$ when $w'_n$ was the current number of W-sequences of $T_j$.

For the W-R check using previous states of $D_i$, the states of $D_i$ then need either to be saved before updating or to be regenerated when checking the conflict. If all the previous states of $D_i$ can be held, no write operations for regenerating the states of $D_i$ is needed for the W-R check. However, it is hardly a practical solution due to the limitation of memory resources. In the following, the term $sn_{max}$ denotes the maximum number of states of $D_i$ that can be held in the system. We assume that the value of $sn_{max}$ can be changed depending on the available size of memory. An algorithm that determines $sn_{max}$ states of $D_i$ providing large effects on subsequent W-R checks is proposed in Section 5.2.

In the following, the proposed method for the W-R check using previous states of $D_i$ is described. We define several notations for the following explanation. The term s-point is used to indicate the point of time that the state of $D_i$ is saved.

- $s_n(\leq sn_{max})$: the current number of s-points.
- $sp(h)$ ($1 \leq h \leq sn$): the $h$-th s-point.
- $D_h$: the state of $D_i$ saved at s-point $sp(h)$.
- $wn_i(h)$ for each $T_i$: the value of $wn_i$ at s-point $sp(h)$.

We say that s-point $sp(h)$ is set in write sequence $WS_i(k)$ for each transaction $T_i$ if $k = wn_i(h)$.

For each R-sequence $RS_j(k)(1 \leq k \leq w_n)$, if there is s-point $sp(h)$ such that $wn_i(h) = k$, then the W-R check against R-accesses in $RS_j(k)$ can be performed using $D_h$. Suppose that there is no s-point $sp(h)$ such that $wn_i(h) = k$. There are two cases to be considered. The first case is that there is s-point $sp(h')$ such that $wn_i(h') = k'$. There is the maximum value with $k' < k$. The second case is that there is no such s-point $sp(h')$. In the first case, the updates until sequence $WS_i(k)$ are reflected in $D_h(k')$. Let $D'_h$ be the state of $D_h(k')$ in which the updates by $T_j$ from $WS_i(k') + 1$ to $WS_i(k)$ are also reflected. In the second case, let $D'_h$ be the state of $D_i$ at all the updates by $T_j$ until W-sequence $WS_i(k)$ are reflected. Then, in the both cases, the W-R check against R-accesses in $RS_j(k)$ can be performed using $D'_h$.

The proposed algorithm for the W-R check is then as follows:

When a transaction $T_j$ requests a W-access $W_i$,

1. Prepare $D$ which is a copy of document $D_i$, and prepare $D'_h$ which is the state of $D_i$ updated by $W_i$.
2. For each transaction $T_j \in T - \{T_i\}$, execute accesses from the first R-sequence to the R-sequence just before $WS_j(wn_i(1))$, i.e., the W-sequence in which the first s-point is set.
3.1 If the access is W-access $W_j$, reflect the update by $W_j$ in document $D$.
3.2 If the access is R-access $R_j$, then check if $Check(D, Merge(D'_h, D), R_j) = ok$. If it holds, then $W_i$ does not conflict with $R_j$, and thus go (2) and execute the next access. Otherwise, $W_i$ conflicts with $R_j$, and thus block $T_i$ until $T_j$ finishes. When $T_j$ finishes, $T_i$ restarts.
3.3 For each s-point $sp(h)$ with $1 \leq h \leq sn$,
3.3.1 Prepare $D$ which is a copy of document $D_h$.
3.3.2 For every transaction $T_i$ and every R-access $R_j$ in $RS_j(wn_i(h))$, check if $Check(D, Merge(D'_h, D), R_j) = ok$. If not so, $W_i$ conflicts with $R_j$ and thus block $T_i$ until $T_j$ finishes. When $T_j$ finishes, $T_i$ restarts.

(3.3) For each transaction $T_j$, if an s-point is not set in W-sequence $WS_j(wn_i(h) + 1)$, execute accesses from $WS_j(wn_i(h) + 1)$ to the R-sequence just before the W-sequence in which s-point $sp(h + 1)$ is set or to the latest R-sequence.

(3.3.1) If the access is W-access $W_j$, reflect the update by $W_j$ in document $D$.
(3.3.2) If the access is R-access $R_j$, then check if $Check(D, Merge(D'_h, D), R_j) = ok$. If it holds, then $W_i$ does not conflict with $R_j$, and thus go (3.3) and execute the next access. Otherwise, $W_i$ conflicts with $R_j$, and thus block $T_i$ until $T_j$ finishes. When $T_j$ finishes, $T_i$ restarts.

The pseudo code of the proposed algorithm for the W-R check based on s-points is shown in Appendix B. Steps 1, 2, and 3 in Appendix correspond to parts (1), (2), and (3) of the above explanation, respectively.

By using the states of $D_i$ that are saved at s-points, the write operations for generating previous states of $D_i$ in subsequent W-R checks are reduced. The number of write operations can be reduced by each s-point $sp(h)$ is referred as $E(h)$ in the following section. (The definition of $E(h)$ and the determination of s-point $sp(h)$ providing a large value of $E(h)$ are given in Section 5.2.) Let $nr_j$ and $nw_i$ be the number of R-accesses and W-accesses in $AS_j$, respectively. In addition, let $cr_j$ and $cw_i$ be the cost of performing an R-access and evaluating function $Check$, and the cost of performing a W-access, respectively. When a W-access $W_i$ is requested, the execution cost needed for the proposed W-R check on s-points is then equal to

$$\sum_{1 \leq j \leq n, i \neq j} (nr_j \times cr_j + nw_i \times cw_i) - \left( \sum_{1 \leq h \leq sn_{max}} E(h) - \sum_{1 \leq h \leq sn_{max}, wn_i(h) \neq wn_i(h - 1)} |WS_i(g)| \times cw_i \right).$$

5.2 Determination of S-Points

This section presents the method to dynamically determine the point of time to save the state of $D_i$. Since $D_i$ is continuously updated, we need to check if the current state of $D_i$ has a large effect on subsequent W-R checks and to determine if setting an s-point. In the following, the way to measure the effect of each s-point, i.e. the effect obtained by saving $D_i$ at the s-point is first described and the algorithm to determine if setting an s-point or not is next given.

Whenever a W-access is requested by transaction $T_i$, after s-point $sp(h)$, the use of $D_i(h)$ can reduce $\sum_{1 \leq i \leq n, j \neq i} |WS_j(wn_i(h))|$ write operations in the W-R check for the W-access. As a consequence, it is considered that the effect obtained by saving the state of $D_i$ at s-point $sp(h)$ is proportional to the sum of the numbers of W-accesses in $WS_i(wn_i(h))$'s with $1 \leq i \leq n$. We define $E(h)$ of a s-point $sp(h)$ as follows:

$$\begin{cases} E(h) = \sum_{1 \leq i \leq n} |WS_i(wn_i(h))|, \\
\text{Otherwise, } E(h) = \sum_{1 \leq i \leq n, wn_i(h) \neq wn_i(h - 1)} |WS_i(wn_i(h))|.
\end{cases}$$

When $h = 1$, i.e., the s-point is the first one, effect $E(h)$ is the sum of the numbers of W-accesses in the recent W-sequences of all transactions. On the other hand, when $h > 1$, the number of W-accesses in $WS_i(wn_i(h))$ is not added to $E(h)$ if $wn_i(h) = wn_i(h - 1)$. In that case, the W-R check against $RS_i(wn_i(h))$ can be performed using either $D_h$ or $D_i(h - 1)$. Thus we add

$$\begin{cases} E(h) = \sum_{1 \leq i \leq n} |WS_i(wn_i(h))|, \\
\text{Otherwise, } E(h) = \sum_{1 \leq i \leq n, wn_i(h) \neq wn_i(h - 1)} |WS_i(wn_i(h))|.
\end{cases}$$

When $h = 1$, i.e., the s-point is the first one, effect $E(h)$ is the sum of the numbers of W-accesses in the recent W-sequences of all transactions. On the other hand, when $h > 1$, the number of W-accesses in $WS_i(wn_i(h))$ is not added to $E(h)$ if $wn_i(h) = wn_i(h - 1)$. In that case, the W-R check against $RS_i(wn_i(h))$ can be performed using either $D_h$ or $D_i(h - 1)$. Thus we add
In addition, we also define the reduced effect, \( E^- (h) \), by deleting s-point \( sp(h) \). For each s-point \( sp(h) \), \( E^- (h) \) is computed as follows: Initially, \( E^- (h) = E(h) \). For each \( T_i \),

1. If \( sp(h) \) is not the latest, \( wn_i(h) = wn_i(h + 1) \), and \((h = 1) \) or \((wn_i(h) \neq wn_i(h - 1)) \), then reduce \( |WS_i(wn_i(h))| \) from \( E^- (h) \). When deleting \( sp(h) \), \( |WS_i(wn_i(h))| \) is then added to \( E(h + 1) \).
2. If \( sp(h) \) is the latest s-point and \( wn_i(h) = wn_i \), then reduce \( |WS_i(wn_i(h))| \) from \( E^- (h) \). When deleting \( sp(h) \), \( |WS_i(wn_i(h))| \) is then added to the effect of a new s-point.

Using effects \( E(h) \) and \( E^- (h) \) as the criteria, a new s-point is set if its effect is larger than the previous s-point having the minimum value, \( E_{min} \), of \( E^- (h) \) \((1 \leq h \leq sn_{max}) \). In the following, \( sp_{min} \) denotes the previous s-point having \( E_{min} \).

We present the proposed method that determines \( sn_{max} \) s-points that provide large effects. Right before \( D_{all} \) is updated by W-accesses in a new W-sequence, the proposed determination of an s-point is performed as follows:

1. Calculate the increased effect, \( E^+ \), by setting a new s-point for saving the current state of \( D_{all} \).
2. If \( sn \), i.e., the current number of s-points is less than \( sn_{max} \), set a new s-point and its effect \( E^+ \).
3. Otherwise, compare \( E^+ \) with \( E_{min} \). If \( E^+ \) is larger than \( E_{min} \), delete s-point \( sp_{min} \) and set a new s-point \( sp(sn_{max}) \). If \( sp_{min} \) is not the latest s-point, effect \( E(sn_{max}) \) of the new s-point is equal to \( E^+ \). Otherwise, \( E(sn_{max}) = E^+ + \epsilon \) \((\epsilon = E(sp_{min}) - E_{min}) \) where \( \epsilon \) is the effect added to the next s-point when s-point \( sp_{min} \) is deleted.

The pseudo code of the proposed algorithm to determine s-points is shown in Appendix C. Steps 1, 2, and 3 in Appendix C correspond to parts (1), (2), and (3) of the above explanation, respectively.

Since a new s-point is always set only when the increased effect by the new s-point is larger than the minimum effect decreased by deleting a previous s-point, the s-point schedule by the proposed algorithm is optimal under the given time-ordered write sequences of transactions.

**Example 3** We illustrate the determination of s-points for the example transactions shown in Fig. 8. In Fig. 8, each times \( t_1, t_2, t_3, \) and \( t_4 \) denote the times right before \( WS_i(1), WS_S(1), WS_S(2), \) and \( WS_i(2) \), respectively. Document \( D(i) \) with \( 1 \leq i \leq 4 \) denotes the state of \( D_{all} \) at time \( t_i \). Assume \( sn_{max} = 2 \). In Fig. 9, we show the scheduling of s-points at each time \( t_i \) \((1 \leq i \leq 4) \) and the information of s-points, i.e. \( wn_i(h) \) for each transaction \( T_i \) \((1 \leq i \leq 3) \), effect \( E(h) \), and \( D_s(h) \) saved at s-point \( sp(h) \).

At times \( t_1 \) and \( t_2 \), s-points are set because two \((= sn_{max}) \) s-points can be set. When the first s-point \( sp(1) \) is set, \( D(1) \) is saved as \( D_s(1) \) and effect \( E(1) \) is \( 1 = wn_1(1) + wn_2(1) + wn_3(1) \), as shown in Fig. 9(1). As shown in Fig. 9(2), when the second s-point \( sp(2) \) is set, \( D(2) \) is saved as \( D_s(2) \). Effect \( E(2) \) equals to \( 3 = wn_2(1) + wn_2(2) \) since \( wn_2(1) = wn_2(2) \) and \( wn_2(3) = wn_2(2) \).

At time \( t_3 \), the number of s-points equals to \( sn_{max} \), and thus it is necessary to determine whether a new s-point is set and s-point \( sp_{min} (= sp(1)) \) is deleted. Effect \( E^- (1) \) reduced by deleting \( sp(1) \) equals to \( 0 \) since \( wn_2(1) \) is added to effect \( E(2) \) of s-point \( sp(2) \) when deleting \( sp(1) \). Effect \( E^+ (= 2) \) increased by setting a new s-point is larger than \( E^- (1) \), and thus a new s-point is set as shown in Fig. 9(3). At time \( t_4 \), s-point \( sp_{min} \) is \( sp(1) \) and effect \( E^- (1) \) equals to \( 0 \). Effect \( E^+ (= 2) \) increased by setting a new s-point is larger than \( E^- (1) \), and thus a new s-point is set as shown in Fig. 9(4).

### 6. Conclusion

In this paper, we proposed a new locking method guaranteeing serializability which supports general XML documents and full XPath Query. The proposed method resolves the phantom problem by adopting a logical locking approach and achieves high concurrency by producing locking at the level of precise data in XML documents. In the proposed method, locks are set on XPath expressions used in transaction accesses and conflicts between the XPath expressions and the updates by different transactions are checked to ensure serializability. To detect conflicts efficiently, we introduced a new data management model, which handles two versions of a document: document \( D_i \) in which updates by each transaction \( T_i \) are reflected and document \( D_{all} \) in which updates by all transactions are reflected. Under our data management model, conflict checks are performed based on XPath evaluation. As for the read-write check when a transaction \( T_i \) requests a read access, XPath expression used in the read access is evaluated on documents \( D_i \) and \( D_{all} \) and the equivalence of nodes in both documents which are reachable by the expression is checked. As for the write-read check, previous states of \( D_{all} \) saved at s-points are used. A dynamic algorithm to determine s-points providing large effects on subsequent write-read checks was also proposed and the proposed s-point schedule was shown to be always optimal in terms of the effect. To evaluate the proposed algorithms for the read-write check and the write-read check, we performed the qualitative analysis of computing costs and
confirmed the effectiveness. The implementation of the proposed method and the quantitative analysis of execution times and memory sizes needed for the proposed locking should be included in future works.

Reference

Appendix
A. Semantics of XPath[10]
\[ S: \text{Axs} \rightarrow \text{Pattern} \rightarrow \text{Node} \rightarrow \text{Set(Node)} \]
- \[ \text{Set(Node)} = \text{Set}([p_1 \cup \ldots \cup p_n]) \]
- \[ \text{Set}([p]) = \text{Set}([\text{root}(x)]) \]
- \[ \text{Set}([p_1 \cup p_2]) = \{x \in \text{Set}([p_1]) \cup \text{Set}([p_2]) \} \]
- \[ \text{Set}([p_1 \cap p_2]) = \{x \in \text{Set}([p_1]) \cap \text{Set}([p_2]) \} \]
- \[ \text{Set}([\text{node}(x)]) = \{x \in \text{Set}([p_1]) \} \]
- \[ \text{Set}([\text{text}(x)]) = \{x \in \text{Set}([p_1]) \} \]
- \[ \text{Set}([\text{string}(x)]) = \{x \in \text{Set}([p_1]) \} \]

B. Algorithm for the write-read check based on s-points

\[ \text{* Step 1: initialization */ } \]
\[ W_i \rightarrow \text{the requested W-access by } T_i \]
\[ D := D_{init} \]
\[ D_i' := \text{GetD}(D_i, W_i); \]

\[ \text{* Step 2: the W-R check for the first R-sequence */ } \]
For each \( T_j \) with \( j < i \) and \( 1 \leq j \leq n \)
\[ l_{end,j} := 0; \]
If \( (k < 0) \) Then \( l_{end,j} := w_{j+1} \)
Else \( \text{if } w_{j+1} + 1 \leq l_{end,j} \) Then \( l_{end,j} := w_{j+1} - 1 \).
For \( l := 0 \) to \( l_{end,j} \): \( l := l + 1 \)
For each \( R_{k} \) in \( R_S(i) \)
\[ \text{If } \text{Check}(D_i, M_{merge}(D_i', D), R_k) \neq \text{ok} \]
\[ \text{Add edge } (T_j \rightarrow T_i) \text{ to the wait-for graph; } \]
\[ \text{Check deadlock; Exit; } \]
\[ \text{EndIF } \]
\[ \text{EndFor } \]
\[ \text{EndIF } \]
\[ \text{EndFor } \]

\[ \text{* Step 3: the W-R check based on s-points */ } \]
For \( (k = 0) \) to \( n \)
For each \( T_j \) with \( j < i \) and \( 1 \leq j \leq n \)
\[ \text{IF } (w_{j+1} > w_{j} + 1) \text{ Then } \]
\[ \text{Check deadlock; Exit; } \]
\[ \text{EndIF } \]
\[ \text{EndFor } \]

C. Algorithm for the determination of s-points

\[ E_{min} = \text{the minimum value of } E'(h) \text{ with } 1 \leq h \leq \text{sn}; \]
\[ s_p(m) := s_p(m_0) \text{ i.e. the s-point having } E'(m) \text{ that } \]
\[ \text{best suits for } m < s_p(m_0); \]
\[ s_p(m) \text{ if } m < s_p(m_0); \]
\[ \text{Add edge } (T_j \rightarrow T_i) \text{ to the wait-for graph; } \]
\[ \text{Check deadlock; Exit; } \]
\[ \text{EndIF } \]
\[ \text{EndFor } \]
\[ \text{EndIF } \]
\[ \text{EndFor } \]