Efficient Support for Ordered XPath Processing in Tree-Unaware Commercial Relational Databases

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Abstract. In this paper, we present a novel ordered XPATH evaluation in *tree-unaware* RDBMS. The novelties of our approach lies in the followings. (a) We propose a novel XML storage scheme which comprises *only* leaf nodes, their corresponding data values, order encodings and their root-to-leaf paths. (b) We propose an algorithm for mapping ordered XPATH queries into SQL queries over the storage scheme. (c) We propose an optimization technique that enforces all mapped SQL queries to be evaluated in a "left-to-right" join order. By employing these techniques, we show, through a comprehensive experiment, that our approach not only scales well but also performs better than some representative tree-unaware approaches on more than 65% of our benchmark queries with the highest observed gain factor being 1939. In addition, our approach reduces significantly the performance gap between tree-aware and tree-unaware approaches and even outperforms a state-of-the-art tree-aware approach for certain benchmark queries.

1 Introduction

Current approaches for evaluating XPATH expressions in relational databases can be arguably categorized into two representative types. They either resort to encoding XML data as tables and translating XML queries into relational queries [1,2,3,4,6,8,11] or store XML data as a rich data type and process XML queries by enhancing the relational infrastructure [5]. The former approach can further be classified into two representative types. Firstly, a host of work on processing XPATH queries on *tree-unaware* relational databases has been reported [3,6,8] – these approaches do not modify the database kernels. Secondly, there have been several efforts on enabling relational databases to be *tree-aware* by invading the database kernel to implement XML support [1,2,4,11]. It has been shown that the latter approaches appear scalable and, in particular, perform orders of magnitude faster than some tree-unaware approaches [1,4].

In this paper, we focus on supporting *ordered* XPATH evaluation in a *tree-unaware* relational environment. There is a considerable benefit in such an approach with respect to portability and ease of implementation on top of an off-the-shelf RDBMS. Although a diverse set of strategies for evaluating XML queries in tree-unaware relational environment have been recently proposed, few have undertaken a comprehensive study on evaluating ordered XPATH queries. Tatarinov *et al.* [9] is the first to show that it is indeed possible to support ordered XPATH queries in relational databases. However, this

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approach does not scale well with large XML documents. In fact, as we shall show in Section 7, the GLOBAL-ORDER approach in [9] failed to return results for 20% of our benchmark queries on 1GB dataset in 60 minutes. Furthermore, this approach resorts to manual tuning of the relational optimizer when it failed to produce good query plans. Although such a manual tuning approach works, it is a cumbersome solution.

In this paper, we address the above limitations by proposing a novel scheme for ordered XPATH query processing. Our storage strategy is built on top of SUCXENT++ [6], by extending it to support efficient processing of ordered axes and predicates. SUCXENT++ is designed primarily for query-mostly workloads. We exploit SUCXENT++'s strategy to store leaf nodes, their corresponding data values, auxiliary encodings and root-to-leaf paths. In contrast, some approaches, *e.g.,* [4,11], explicitly store information for all nodes of an XML document. Specifically, the followings remark the novelties of our storage scheme. (1) For each level of an XML document, we store an attribute called RValue which is an enhancement of the original RValue, proposed in [6], for processing recursive XPATH queries. (2) For each leaf node we store three additional attributes namely BranchOrder, DeweyOrderSum and SiblingSum. These attributes are the foundation for our ordered XPATH processing. The key features of these attributes are that they enable us (a) to compare the order between non-leaf nodes by comparing the order between their *first descendant leaf* nodes only; and (b) to determine the nearest common ancestor of two leaf nodes efficiently. As a result, it is not necessary to store the order information of non-leaf nodes. Furthermore, given any pair of nodes, these attributes enable us to evaluate position-based predicates efficiently.

As highlighted in [9], relational optimizers may sometimes produce poor query plans for processing XPATH queries. In this paper, we undertake a novel strategy to address this issue. As opposed to manual tuning efforts, we propose an *automatic* approach to enforce the optimizer to replace previously generated poor plans with probably better query plans, as verified by our experiments. Unlike tree-aware schemes, our technique is *non-invasive* in nature. That is, it can easily be incorporated *without modifying the internals* of relational optimizers. Specifically, we enforce a relational optimizer to follow a *"left-to-right"* join order and enforce the relational engine to evaluate the mapped SQL queries according to the XPATH steps specified in the query. The good news is that this technique can select better plans for the majority of our benchmark queries across all benchmark datasets. As we shall see in Section 7, the performance of previously-inefficient queries in SUCXENT++ is significantly improved. The highest observed gain factor is 59. Furthermore, queries that failed to finish in 60 minutes were able to do so now, in the presence of such a join-order enforcement. This is indeed stimulating as it shows that some sophisticated internals of relational optimizers not only are irrelevant to XPATH processing but also often confuse XPATH query optimization in relational databases. Overall a "join-order conscious" SUCXENT++ significantly outperforms both GLOBAL-ORDER and SHARED-INLINING[8] in at least 65% of the benchmark queries with the highest observed gain factors being 1939 and 880, respectively. To the best of our knowledge, this is the first effort on exploiting a non-invasive automatic technique to improve query performance *in the context of* XPATH *evaluation in relational environment.*

Recently, [1] showed that MONETDB is among the most efficient and scalable tree-aware relational-based XQuery processor and outperforms the current generation of XQuery systems significantly. Consequently, we investigated how our proposed technique compared to MONETDB. Our study revealed some interesting results. First, although MONETDB is 11-164 and 3-74 times faster than GLOBAL-ORDER and SHARED-INLINING, respectively, for the majority of the benchmark queries, this performance gap is significantly reduced when MONETDB is compared to SUCXENT++. Our results show that not only MONETDB is now 1.3-16 times faster than SUCXENT++ with join-order enforcement but surprisingly our approach is faster than MONETDB for 33% of benchmark queries! Additionally, MONETDB (Win32 builds) failed to shred 1GB dataset as it is vulnerable to the virtual memory fragmentation in Windows environment. This is in contrary to the results in [1] where MONETDB was built on top of Linux 2.6.11 operating system (8GB RAM), using a 64-bit address space, and was able to efficiently shred 11GB dataset.

2 Related Work

Most of the previous tree-unaware approaches, except [9], focused on proposing efficient evaluation for `children` and `descendant-or-self` axes and positional predicates in XPATH queries. In this paper, the main focus is on the evaluation for `following`, `preceding`, `following-sibling`, and `preceding-sibling` axes as well as *position-based* and *range* predicates. All previous approaches, reported query performance on small/medium XML documents – smaller than 500 MB. We investigate query performance on large synthetic and real datasets. This gives insights on the scalability of the state-of-the-art tree-unaware approaches for ordered XML processing.

Compared to the tree-aware schemes [1,2,4,11], our technique is *tree-unaware* in the sense that it can be built on top of any commercial RDBMS without modifying the database kernel. The approaches in [2,11] do not provide a systematic and comprehensive effort for processing ordered XPATH queries. Although the scheme presented in [1,2,4] can support ordered axes, no comprehensive performance study has demonstrated with a variety of ordered XPATH queries. Furthermore, these approaches did not exploit the "left-to-right" join order technique to improve query plan selection.

In [9], Tatarinov *et al.* proposed the first solution for supporting ordered XML query processing in a relational database. A modified EDGE table [3] was the underlying storage scheme. They described three order encoding methods: *global*, *local*, and *dewey* encodings. The best query performance was achieved with the *global* encoding for query-mostly workloads and with *dewey* encoding for a mix of queries and updates. Our focus differs from the above approach in the following ways. First, we focus on query-mostly workloads. Second, we consider a novel order-conscious storage scheme that is more space- and query-efficient and scalable when compared to the *global* encoding.

3 Background on SUCXENT++

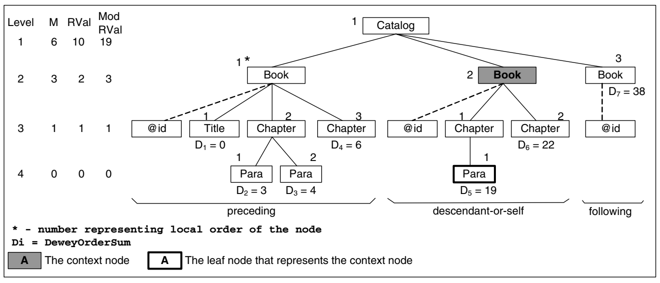
Our approach for ordered XPATH processing relies on the SUCXENT++ approach [6]. We begin our discussion by briefly reviewing the storage scheme of SUCXENT++.

```
Document (DocId, Name)
Path (PathId, PathExp)
PathValue(DocId, PathId, LeafOrder,
  BranchOrder, BranchOrderSum,
  LeafValue)
DocumentRValue (DocId, Level, RValue)
```

(a) Original Schema of SUCXENT++

```
Document (DocId, Name)
Path (PathId, PathExp)
PathValue(DocId, DeweyOrderSum,
  PathId, BranchOrder, LeafOrder,
  SiblingSum, LeafValue)
Attribute (DocId, LeafOrder, PathId,
  LeafValue)
DocumentRValue (DocId, Level, RValue)
```

(b) Modified Schema of SUCXENT++



(c) XML Data

Fig. 1. Example of XML data and SUCXENT++ schema

Foremost, in the rest of the paper, we always assume *document order* in our discussions. The SUCXENT++ schema is shown in Figure 1(a). Document stores the document identifier DocId and the name Name of a given input XML document T. We associate each distinct (root-to-leaf) path appearing in T, namely PathExp, with an identifier PathId and store this information in Path table. For each leaf node n in T, we shall create a tuple in the PathValue table. We now elaborate the meaning of the attributes of this relation.

Given two leaf nodes n_1 and n_2, n_1.LeafOrder $<$ n_2.LeafOrder *iff* n_1 precedes n_2. LeafOrder of the first leaf node in T is 1 and n_2.LeafOrder = n_1.LeafOrder+1 *iff* n_1 is a leaf node immediately preceding n_2. Given two leaf nodes n_1 and n_2 where n_1.LeafOrder+1 = n_2.LeafOrder, n_2.BranchOrder is the level of the nearest common ancestor of n_1 and n_2. That is, n_1 and n_2 *intersect* at the BranchOrder level. The data value of n is stored in n.LeafValue.

To discuss BranchOrderSum and RValue, we introduce some auxiliary definitions. Consider a sequence of leaf nodes C: $\langle n_1, n_2, n_3, \ldots, n_r \rangle$ in T. Then, C is a *k-consecutive leaf nodes* of T *iff* (a) n_i.BranchOrder $\geq k$ for all $i \in [1,r]$; (b) If n_1.LeafOrder > 1, then n_0.BranchOrder $< k$ where n_0.LeafOrder+1 = n_1.LeafOrder; and (c) If n_r is not the last leaf node in T, then n_{r+1}.BranchOrder $< k$ where n_r.LeafOrder+1 = n_{r+1}.LeafOrder. A sequence C is called a *maximal k-consecutive leaf nodes* of T, denoted as M_k, if there does not exist a k-consecutive leaf nodes C' and $|C|<|C'|$.

Let L_{max} be the largest level of T. Then, RValue of level ℓ, denoted as R_ℓ, is 1 if $\ell = L_{max}$. Otherwise, $R_\ell = R_{\ell+1} \times |M_{\ell+1}| + 1$. Now we are ready to define the BranchOrderSum attribute. Let N to be the set of leaf nodes preceding a leaf node n. n.BranchOrderSum is 0 if n.LeafOrder = 1 and $\sum_{m \in N} R_{m.BranchOrder}$ otherwise.

Based on the definitions above, Prakash *et al.* [6] defined Property 1 (below) which is essential to determine ancestor-descendant relationships efficiently.

Property 1. Given two leaf nodes n_1 and n_2, $|n_1$.BranchOrderSum - n_2.BranchOrderSum$|$ $< R_\ell$ *implies the nearest common ancestor of n_1 and n_2 is at a level greater than ℓ.* $\square$

4 Extensions of SUCXENT++

To support ordered XML queries, the order information of nodes must be captured in the XML storage scheme. Unfortunately the LeafOrder and BranchOrderSum attributes only encode the global order of all leaf nodes. Since (order) information of non-leaf nodes is not explicitly stored, it must be derived from the attributes of leaf nodes. We now present how the original SUCXENT++ schema is extended to process ordered XPath queries efficiently. The modified schema is shown in Figure 1(b).

4.1 Attribute Table

The PathValue table originally stored information related to both element and attribute nodes. However, to avoid mixing the order of element and attribute nodes, we separate the attribute nodes into Attribute table. The Attribute table consists of the following columns: DocId, LeafOrder, PathId, LeafValue. As we shall see later, a non-leaf node can be represented by the first descendant leaf nodes. Therefore, an attribute node is identified by DocId and LeafOrder of its parent node and its PathId.

4.2 Modified RValue Attribute

Conceptually, RValue is used to encode the level of the nearest common ancestor of any pairs of leaf nodes. To ensure a property like Property 1 holds after modifications, intuitively, we "magnify" the gap between RValues, as shown in Definition 1. Relative order information is then captured in these gaps.

Definition 1 [ModifiedRValue]. *Let L_{max} be the largest level of an* XML *tree T.* ***ModifiedRValue*** *of level ℓ, denoted as R'_ℓ, is defined as follows: (i) If $\ell = L_{max} - 1$ then $R'_\ell = 1$ and $|M_\ell| = 1$; (ii) If $0 < \ell < L_{max} - 1$ then $R'_\ell = 2R'_{\ell+1} \times |M_{\ell+1}| + 1$.* □

To ensure the evaluation of queries other than ordered XPATH queries is not affected by the above modifications, the RValue attribute in DocumentRValue stores $\frac{R'_\ell - 1}{2} + 1$ instead of R'_ℓ.

4.3 DeweyOrderSum and SiblingSum Attributes

Next, we define the first attribute related to ordered XPATH processing. Consider the path query `/catalog/book[1]/chapter[1]` and Figure 1(c). Since only leaf nodes are stored in the PathValue table, the new attribute DeweyOrderSum of leaf nodes captures order information of the non-leaf nodes. At first glance, a simple representation of the order information could be a Dewey path. For instance, the Dewey path of the first `chapter` node of the first `book` node is "1.1.2". However, using such Dewey paths has two major drawbacks. Firstly, string matching of Dewey paths can be computationally expensive. Secondly, simple lexicographical comparisons of two Dewey paths may not always be accurate [9]. Hence, we define DeweyOrderSum for this purpose:

Definition 2 [DeweyOrderSum]. *Consider an* XML *document T and a leaf node n at level ℓ in T.* $\text{Ord}(n, k) = i$ iff *a is either an ancestor of n or n itself; k is the level of a; and a is the i-th child of its parent.* DeweyOrderSum *of n, n.*DeweyOrderSum, *is defined as $\sum_{j=2}^{\ell} \Phi(j)$ where $\Phi(j)$=[$\text{Ord}(n, j)$-1]$\times R'_{j-1}$.* □

For example, consider the rightmost `chapter` node in Figure 1(c) which has a Dewey path “1.2.2”. DeweyOrderSum of this node is: n.DeweyOrderSum $= (Ord(n, 2) - 1) \times R'_1 + (Ord(n, 3) - 1) \times R'_2 = 1 \times 19 + 1 \times 3 = 22$. Note that DeweyOrderSum is not sufficient to compute position-based predicates with `QName` name tests, *e.g.*, `chapter`[2]. Hence, the SiblingSum attribute is introduced to the PathValue table.

Definition 3 [SiblingSum]. *Consider an* XML *document T and a leaf node n at level ℓ in T.* Sibling(n, k) = i iff *a is either an ancestor of n or n itself; k is the level of a; and the i-th τ-child of its parent (τ is the tag name of a).* SiblingSum *of n, n.*SiblingSum*, is $\sum_{j=2}^{\ell} \Psi(j)$ where $\Psi(j)$ = [*Sibling(n, j)*-1]$\times R_{j-1}$.* □

SiblingSum encodes the local order of nodes which are with the same tag name of n, namely same-tag-sibling order. For example, consider the children of the first `book` element in Figure 1(c). The local orders of `title` and the first and second `chapter` nodes are 1, 2 and 3, respectively. On the other hand, the same-tag-sibling order of these nodes are 1, 1 and 2, respectively.

4.4 Preservation of SUCXENT++’s Features

The above modifications do not adversely affect the document reconstruction process and efficient evaluation of non-ordered XPATH queries, as discussed in [6]. Recall that given a pair of leaf nodes, Property 1 was used in [6] to efficiently determine the nearest common ancestor of the nodes. Since we have modified the definition of RValue and replaced the BranchOrderSum attribute with the DeweyOrderSum attribute, this property is not applicable to the extended SUCXENT++ scheme. It is necessary to ensure that a corresponding property holds in the extended system.

Theorem 1. *Let n_1 and n_2 be two leaf nodes in an* XML *document. If $\frac{R'_{\ell+1}-1}{2} + 1 < |n_1.\text{DeweyOrderSum - } n_2.\text{DeweyOrderSum}| < \frac{R'_{\ell}-1}{2} + 1$ then the level of the nearest common ancestor of n_1 and n_2 is $\ell + 1$.* □

Due to space constraints, the proofs and examples of the theorems and propositions discussed in this paper are given in [7].

5 Ordered XPath Processing

Our strategy for comparing the order of non-leaf nodes is based on the following observation. If node n_0 precedes (resp. follows) another node n_1, then descendants of n_0 must also precede (resp. follow) the descendants of n_1. Therefore, instead of comparing the order between non-leaf nodes, we compare the order between *their descendant leaf nodes.* For this reason, we define the *representative leaf node* of a non-leaf node n to be its first descendant leaf node. Note that the BranchOrder attribute records the level of the nearest common ancestor of two consecutive leaf nodes. Let C be the sequence of descendant leaf nodes of n and n_1 be the first node in C. We know that the nearest common ancestor of any two consecutive nodes in C is also a descendant of node n. This implies (1) except n_1, BranchOrder of a node in C is at least the level of node n

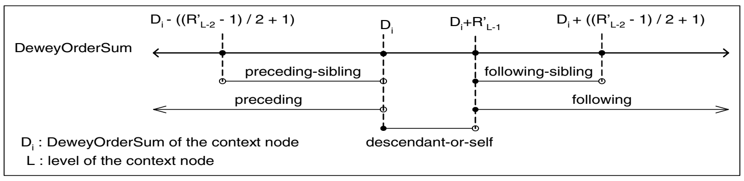

D_i - ((R'_{L-2} - 1) / 2 + 1)
D_i
D_i+R'_{L-1}
D_i + ((R'_{L-2} - 1) / 2 + 1)
DeweyOrderSum
preceding-sibling
following-sibling
preceding
following
descendant-or-self
D_i : DeweyOrderSum of the context node
L : level of the context node

Fig. 2. Relationship between DeweyOrderSum and RValue

and (2) the nearest common ancestor of n_1 and its immediately preceding leaf node is not a descendant of node n. Therefore, BranchOrder of n_1 is always smaller than the level of n. We summarize this property in Property 2.

*Property 2. Let n be a non-leaf node at level ℓ and $C = \langle n_1, n_2, n_3, \ldots, n_r \rangle$ be the sequence of descendant leaf nodes of n in document order. Then, n_1.*BranchOrder $< \ell$ *and n_i.*BranchOrder $\geq \ell$, *where $i \in (1,r]$.* □

Definition 4 [DeweyOrderSum of non-leaf nodes]. *Let $S = \langle i_1, i_2, i_3, \ldots, i_{r_1} \rangle$ be a sequence of non-leaf sibling nodes of a non-leaf node i_0 in document order. Let $C = \langle n_1, n_2, \ldots, n_{r_2} \rangle$ be the sequence of leaf nodes of S and n_{j_2} is denoted as the first descendant leaf node of i_{j_1}. Then, i_{j_1}.*DeweyOrderSum $= n_{j_2}$.DeweyOrderSum. □

In the above definition, DeweyOrderSum of a leaf node is *conceptually* propagated to its ancestor nodes. Consequently, the following proposition holds.

Proposition 1. *Let $C = \langle n_1, n_2, n_3, \ldots, n_r \rangle$ be a sequence of sibling nodes. Consider n_i where $1 < i \leq r$ and the level of n_i is ℓ, where $\ell > 1$. Let m be n_i or a descendant of n_i. Then, n_1.*DeweyOrderSum$+$ *[*Ord*(n_i) -* Ord*(n_1)] $\times R'_{\ell-1} \leq m$.*DeweyOrderSum $<$ n_1.DeweyOrderSum$+$ *[(*Ord*(n_i) -* Ord*(n_1))+1] $\times R'_{\ell-1}$ where* Ord*(n_i) and* Ord*(n_1) are the local order of n_i and n_1, respectively.* □

By using the above proposition, we can compare the order of two non-leaf nodes without evaluating every sibling nodes in the sequence. Similar propositions for SiblingSum can be established in a straightforward manner.

5.1 Support for Ordered XPath Queries

We now present how various types of ordered XPATH queries are supported by the modified SUCXENT++. Due to space constraints, we only focus on how DeweyOrderSum and ModifiedRValue are used for query processing. Similar technique can be applied to evaluations with SiblingSum.

Position predicates. Position-based predicates, *i.e.,* predicates of the form position()=i, select the node at the i-th position of the sequence of *inner focus context nodes*. We propose to compute the i-th node without evaluating every node in the sequence by applying Proposition 1. For example, suppose n_1 be the first `book` node of the sequence of `book` nodes (the context nodes) in Figure 1(c). Observe that n_1.DeweyOrderSum $= 0$ as its representative leaf node is the first leaf node of the XML tree. We now employ the inequality in Proposition 1 to select a sibling node, *e.g.,* the second `book` node n_2. Here, $\mathsf{Ord}(n_2) = 2$, $\ell = 2$, $R'_1 = 19$, and $n_1.\mathsf{DeweyOrderSum} = 0$. Then, $0 + 1 \times 19 \leq n_2.\mathsf{DeweyOrderSum} < 0 + 2 \times 19 \Rightarrow 19 \leq n_i.\mathsf{DeweyOrderSum} < 38$. The nodes in this range are the descendant leaf nodes of n_2. Such simple arithmetic calculations can be efficiently implemented in a relational database.

The range operator, *e.g.*, `[position()=2 TO 10]`, can be easily handled in a similar fashion. $\mathsf{fn} : \mathsf{last}()$ can be computed by first determining all sibling nodes that satisfy the specific path and then finding the node with the largest DeweyOrderSum.

Following and preceding axes. `following` axis selects all nodes which follow the context node excluding the descendants of the context node. `preceding` axis, on the other hand, selects all nodes which precede the context node excluding the ancestors of the context node. Similar to position predicates, we summarize a property of DeweyOrderSum to facilitate efficient processing of these axes. Proofs and additional examples are given in [7].

Proposition 2. *Let n_a and n_b be two nodes in the* XML *tree T and n_b is a context node at level ℓ_b where $\ell_b > 1$. Then, the following statements hold:*

1. $n_a.\mathsf{DeweyOrderSum} \geq n_b.\mathsf{DeweyOrderSum} + R'_{\ell_{b-1}}$ *if and only if n_a follows n_b and is not a descendant of n_b;*
2. *Similarly,* $n_a.\mathsf{DeweyOrderSum} < n_b.\mathsf{DeweyOrderSum}$ *if and only if n_a precedes n_b and n_a is neither a descendant nor an ancestor of n_b.*

$\square$

Following-sibling and preceding-sibling axes. `following-sibling` axis selects the children of the context node's parent that occur after the context node in document order whereas `preceding-sibling` axis selects the children of the context node's parent that occur before the context node in document order. Support for `following-sibling` (resp. `preceding-sibling`) axis can be achieved with an additional constraint on the `following` (resp. `preceding`) axis – the selected nodes must be siblings of the context node.

Proposition 3. *Let n_a and n_b be two nodes in the* XML *tree T and n_b is the context node at level ℓ_b where $\ell_b > 2$. Then, the following statements hold:*

1. $n_b.\mathsf{DeweyOrderSum} + R'_{\ell_b-1} \leq n_a.\mathsf{DeweyOrderSum} < n_b.\mathsf{DeweyOrderSum} + (R'_{\ell_b-2} - 1)/2 + 1$ *and if and only if n_a is a sibling of n_b and n_a follows n_b.*
2. $n_b.\mathsf{DeweyOrderSum} - (R'_{\ell_b-2} - 1)/2 - 1 < n_a.\mathsf{DeweyOrderSum} < n_b.\mathsf{DeweyOrderSum}$ *if and only if n_a is a sibling of n_b and n_a precedes n_b.*

$\square$

The above proposition can be illustrated with the following example. Suppose we evaluate the `following-sibling` axis on the first `title` node n_t in Figure 1(c). Here $n_t.\mathsf{DeweyOrderSum} = 0$, $\ell = 3$, $R'_1 = 19$, and $R'_2 = 3$. Denote N to be the nodes reachable via the `following-sibling` axis from n_t. Using Proposition 3, $0 + 3 \leq n_k.\mathsf{DeweyOrderSum} < 0 + (19 - 1)/2 + 1$ where $n_k \in N$. That is, $3 \leq n_k.\mathsf{DeweyOrderSum} < 10$. Hence, the second (DeweyOrderSum = 3) and the third (DeweyOrderSum = 6) `chapters` are in this range.

We illustrate Proposition 2 and Proposition 3 with Figure 2. An example can be found in Figure 1(c).

```
processPathExpr (XPath)

01 for every step in the XPath {
02   if (step.getAxis() == CHILD and
              step.hasPredicate() == FALSE)
03     currentPath.add(nametest, step.getAxis())
04   else {
05     from_sql.add("PathValue as V_i")
06     if(currentPath.level() > 1) {
07       where_sql.add("V_i.pathid in currentPath.getPathId()")
08       where_sql.add("V_i.branchOrder < currentPath.level()")
09     }
10     processAxis(step, currentPath)
11     processPredicate(step, currentPath)
12   }
13   if (step.isLast() and currentPath.needUpdate()) {
14     from_sql.add("PathValue as V_i")
15     where_sql.add("V_i.pathid in currentPath.getPathId()")
16   }
17 }
18 select_sql.add("V_i.leafValue, V_i.leafOrder, ... ")
19 return select_sql + from_sql + where_sql +
         where_sql.unionWithAttribute()
```

(a)The processPathExpr Algorithm

```
processAxis (step, currentPath)

01 switch (step.getAxis()){
02   child:
03     where_sql.add("V_i.DeweyOrderSum BETWEEN
            V_{i-1}.DeweyOrderSum - RValue(currentPath.level() - 1) + 1 AND
            V_{i-1}.DeweyOrderSum + RValue(currentPath.level() - 1) - 1 ")
04   following:
05     where_sql.add("V_i.DeweyOrderSum >=
            V_{i-1}.DeweyOrderSum + 2 * RValue(currentPath.level()) - 1 ")
06   preceding:
07     where_sql.add("V_i.DeweyOrderSum < V_{i-1}.DeweyOrderSum ")
08   following-sibling:
09     where_sql.add("V_i.DeweyOrderSum BETWEEN
            V_{i-1}.DeweyOrderSum + 2 * RValue(currentPath.level()) - 1 AND
            V_{i-1}.DeweyOrderSum + RValue(currentPath.level() - 1) - 1 ")
10   preceding-sibling:
11     where_sql.add("V_i.DeweyOrderSum BETWEEN
            V_{i-1}.DeweyOrderSum - RValue(currentPath.level() - 1) + 1 AND
            V_{i-1}.DeweyOrderSum - 1 ")
12 }
13 currentPath.add(nametest, step.getAxis())
```

(b)The processAxis Algorithm

Fig. 3. Procedure `processPathExpr` and Procedure `processAxis`

```
processPredicate (step, currentPath)

01 switch (step.getAxis()) {
02   CHILD:
03      n_from = step.getPredicateFrom() - 1
04      n_to   = step.getPredicateTo()
05   FOLLOWING-SIBLING:
06      n_from = step.getPredicateFrom()
07      n_to   = step.getPredicateTo() + 1
08   PRECEDING-SIBLING:
09      n_from = - step.getPredicateFrom()
10      n_to   = - step.getPredicateTo() + 1
11 }
12 switch (step.getPredicateType()){
13   position based predicate without name test:
14      where_sql.add("V_i.DeweyOrderSum BETWEEN
          V_{i-1}.DeweyOrderSum + n_from *
          (2 * RValue(currentPath.level()) - 1) AND
          V_{i-1}.DeweyOrderSum + n_to *
          (2 * RValue(currentPath.level()) - 1) - 1 ")
15   position based predicate with name test:
16      where_sql.add("V_i.SiblingSum BETWEEN
          V_{i-1}.SiblingSum + n_from *
          (2 * RValue(currentPath.level()) - 1) AND
          V_{i-1}.SiblingSum + n_to *
          (2 * RValue(currentPath.level()) - 1) - 1 ")
17 }
```

(a)The processPredicate Algorithm

```
01  WITH V (leafValue, pathID, branchOrder, DeweyOrderSum,
            DocId, LeafOrder  ) AS (
02  SELECT DISTINCT V2.leafValue, V2.pathID, V2.branchOrder,
                    V2.DeweyOrderSum, V2.DocId, V2.LeafOrder
03    FROM PathValue V1, PathValue V2
04    WHERE V1.docId = 1
05    AND V1.pathid in (5,4,3,2)
06    AND V1.SiblingSum BETWEEN
           0 + 1 * (2 * 10 - 1) AND
           0 + 2 * (2 * 10 - 1) - 1
07    AND V1.branchOrder < 2
08    AND V2.docId = V1.docId
09    AND V2.pathid in (5,4,3,2)
10    AND V2.DeweyOrderSum >= V1.DeweyOrderSum + 2 * 10 - 1
11    AND V2.DeweyOrderSum BETWEEN
              V1.DeweyOrderSum + 1 * (2 * 10 - 1)  AND
              V1.DeweyOrderSum + 2 * (2 * 10 - 1) - 1
12  )
13  SELECT V.*, 1 AS Attr
14    FROM V
15  UNION ALL
16  SELECT A.leafValue, A.pathID, V.branchOrder, V.DeweyOrderSum,
           A.DocId, A.LeafOrder, 0 AS Attr
17    FROM Attribute A, V
18    WHERE A.DocId = V.DocId AND A.LeafOrder = V.LeafOrder
19    AND A.PathId in (1)
20  ORDER BY DocId, DeweyOrderSum, Attr
```

(b) SQL Example

Fig. 4. Procedure `processPredicate` and SQL example

5.2 Ordered XPath Query Translation Algorithm

Based on the properties defined in the previous subsection, we present an algorithm, shown in Figures 3 and 4, for generating SQL from ordered XPATH queries. Our algorithm assumes an XPATH expression is represented as a sequence of steps where a step may be associated with predicates. A SQL statement consists of three clauses: $select\_sql$, $from\_sql$ and $where\_sql$. We assume that a clause has an `add()` method which encapsulates some simple string manipulations and simple SUCXENT++ joins for constructing valid SQL statements. In addition to preprocessing PathId as mentioned in [6], for a single XML document, we also preprocess RValue to reduce the number of joins. The translation consists of three main procedures.

`processPathExpr` **(Figure 3(a)):** It analyzes the steps of an input XPATH expression (Line 01) and outputs a SQL statement. If the step consists of a child axis only (Lines 02-03), then we simply maintain a global variable $currentPath$ which records the simple downward path from the root to the context nodes.[1] Otherwise, when the step involves ordered predicates/other axes, we add predicates which select a superset of the next context nodes (Lines 05-09) and then call `processAxis` and `processPredicate` (Lines 10-11) with $currentPath$ to obtain the next context

[1] The details for maintaining $currentPath$ is simple but lengthy. For simplicity, we omitted such discussions.

nodes. We add predicates in Lines 08 to determine the representative nodes of the context nodes. Finally, we collect the final results (Line 19).

`processAxis` **(Figure 3(b)):** This procedure translates a step, together with $currentPath$, based on the step type (Line 01). Lines 02-03, 04-07 and 08-11 encode Theorem 1, Proposition 2 and Proposition 3, respectively.

`processPredicate` **(Figure 4(a)):** This procedure mainly translates position predicates. Lines 01-11 determine the range of position specified by the predicate. Given these, Lines 12-17 implement Proposition 1.

We now illustrate the details of the translation algorithms with an example related to the translation of position-based predicates. Please refer to [7] for more examples. Consider the path expression `/catalog/book[2]/following-sibling::*[1]`. The translated SQL is shown in Figure 4(b). `/catalog/book[2]` is translated into Lines 05-07. `/following-sibling::*` is translated into Lines 08-10, and `*[1]` is translated into Line 11. Lines 13-14 and 16-19 are used to retrieve the resulting element nodes and their attribute nodes, respectively. The last line is to sort the result nodes in document order.

6 Join Order Enforcement

Due to the tree-unaware nature of the underlying relational storage scheme as well as the lack of appropriate XML statistics, relational optimizers may generate inefficient query plans. In order to address this problem, some approaches have resorted to manual tuning of query plans [9] while others invade the database kernel to make it tree-aware [1,2]. The former approach has not been scalable as it requires significant human intervention whereas the later approach may require non-trivial modifications of the internals of a RDBMS. In this section, we propose a simple yet effective technique to generate better query plans automatically *without invading the database kernel.*

As discussed in Section 5.2, in order to evaluate an (ordered) XPATH query in SUCXENT++, each XPATH axis is translated into a join between the PathValue table and intermediate results (*i.e.,* the context nodes). For example, in Figure 4(b), PathValue V1 returns the representative nodes of the context nodes to calculate PathValue V2. Due to the lack of tree awareness, the relational optimizer is not capable of transforming the order of joins intelligently. Consequently, it may generate poor join order that typically requires caching large intermediate results in the database bufferpool. This is particularly important to NL joins, where large and deep loops are prohibitive. For example, the first few joins of a "right-to-left" join order may easily yield a large number of context nodes. To respond to this, we propose to enforce a "left-to-right" join order on the translated SQL query. Also, this evaluation order "naturally corresponds" to the order of XPATH steps specified in the XPATH expression. By employing this technique, the relational optimizer does not explore the large number of permutations of join order. We apply join order if the translated SQL query involves more than one PathValue relation. In addition, if the PathValue table appears in the SQL query only once, we let the relational optimizer to decide the plan for the join between the PathValue table and the Attribute table.

The above enforcement can easily be implemented by *query hints* in commercial databases. Regarding our implementation, we use `OPTION(FORCE ORDER)` to

ID	Total Number			Size (MB)	Max Depth
	Node	Attribute	Total		
DC10	225,234	15,000	240,234	10.3	8
DC100	2,242,200	150,000	2,392,200	103.3	8
DC1000	22,442,612	1,500,000	23,942,612	1033.3	8
DBLP	8,222,945	1,665,930	9,888,875	335	6

(a) Features of Dataset

ID	Query	Res. Card.
D1	/dblp/*[100000]/author	2
D2	/dblp/article/author[2]	190,838
D3	/dblp/*[600000]/pages/preceding-sibling::*	6
D4	/dblp/*[600000]/pages/following-sibling::*	5

(c) Benchmark queries for DBLP

ID	Query	Res. Card. (10MB)	Res. Card. (100MB)	Res. Card. (1000MB)
Q1	/catalog/item[1000]	66	119	74
Q2	/catalog/*[1000]	66	119	74
Q3	/catalog/item[position()=1000 to 10000]/ *[position()=2 to 7]	104,272	626,812	627,200
Q4	/catalog/item[position()=1000 to 10000]/authors/ author	65,161	392,930	393,350
Q5	/catalog/*[1500]/publisher/following-sibling::*	30	34	34
Q6	/catalog/*[1500]/publisher/following-sibling::*[5]	7	7	7
Q7	/catalog/*[1500]/publisher/preceding-sibling::*	21	37	54
Q8	/catalog/*[1500]/publisher/preceding-sibling::*[2]	19	35	52
Q9	/catalog/*[X]/following::title	250	2,500	25,000
Q10	/catalog/*[Y]/preceding::title	249	2,499	24,499

X = 2250, 22500, 225000 for DC10, DC100, DC1000 respectively; Y = 250, 2500, 25000 for DC10, DC100, DC1000 respectively

(b) Benchmark queries for DC10, DC100, and DC1000

Fig. 5. Dataset and Benchmark Queries

implement the above technique in SUCXENT++. The strength of this approach lies in its simplicity in implementing on any commercial RDBMS that supports query hints.

7 Performance Study

In this section, we present the results of our performance evaluation on our proposed approach, a tree-unaware schema-oblivious approach (GLOBAL-ORDER [9]), a tree-unaware schema-conscious approach (SHARED-INLINING [8]), and a tree-aware approach (MonetDB [1]). Prototypes for modified SUCXENT++ (denoted as SX), SUCXENT++ with join order enforcement (denoted as SX-JO), GLOBAL-ORDER (denoted as GO) and SHARED-INLINING (denoted as SI) were implemented with JDK 1.5. We used the Windows version of MONETDB/XQuery 0.12.0 (denoted as MXQ) downloaded from http://monetdb.cwi.nl/XQuery/Download/index.html. The experiments were conducted on an Intel Xeon 2GHz machine running on Windows XP with 1GB of RAM. The RDBMS used was Microsoft SQL Server 2005 Developer Edition. Note that we did not study the performance of XML support of SQL Server 2005 as it can only evaluate the first two ordered queries in Figure 5(b).

Data and query sets. In our experiments, XBENCH [10] dataset was used for synthetic data. Data-centric (DC) documents were considered with data sizes ranging from 10MB to 1GB. In addition, we used a real dataset, namely DBLP XML [12]. Figure 5 (a) shows the characteristics of the datasets used. Two sets of queries were designed to cover different types of ordered XPATH queries. In additional, the cardinality of the results was varied. Figures 5 (b) and 5 (c) show the benchmark queries on XBENCH and DBLP, respectively. XPATH queries with descendant axes were not included as they had been studied in [6].

Test methodology. The XPATH queries were executed in the *reconstruct* mode where not only the non-leaf nodes, but also all their descendants, were selected. Appropriate indexes were constructed for all approaches (except for MONETDB) through a careful analysis on the benchmark queries. Prior to our experiments, we ensured that statistics on relations were collected. The bufferpool of the RDBMS was cleared before each run. Each query was executed 6 times and the results from the first run were always discarded.

ID	DC10					DC100					DC1000			
	MXQ	SI	GO	SX	SX-JO	MXQ	SI	GO	SX	SX-JO	SI	GO	SX	SX-JO
Q1	44.17	1,042.33	843.17	58.33	58.33	80.50	5,967.00	13,177.17	47.67	47.67	39,152.67	85,223.50	61.67	61.67
Q2	36.17	1,041.17	862.33	27.67	27.67	114.67	5,967.00	7,653.67	60.33	60.33	39,152.67	86,271.17	44.50	44.50
Q3	492.33	4,935.33	7,163.00	75,236.00	5,885.00	3,023.67	31,229.50	43,517.67	DNF	47,664.17	64,976.50	134,293.83	DNF	368,666.00
Q4	226.50	3,138.83	4,517.33	2,726.00	2,726.00	1,364.33	17,574.33	30,352.50	14,266.33	14,266.33	44,738.67	286,369.00	56,665.17	56,665.17
Q5	41.83	385.33	1,359.67	13.00	28.17	85.83	1,740.67	7,176.50	5,133.67	209.00	7,563.33	1,026.17	49,795.33	1,036.67
Q6	41.50	41.17	1,233.67	63.67	72.83	88.67	437.67	7,121.67	339.00	248.50	1,951.00	889.83	54,927.67	925.67
Q7	36.33	708.67	1,594.00	63.67	78.50	81.17	4,223.33	7,161.33	5,236.20	208.20	30,292.83	908.17	50,419.83	1,000.50
Q8	39.00	688.17	1,556.33	125.67	35.67	85.83	3,522.17	7,301.83	365.83	222.83	6,702.00	868.67	54,610.83	1,144.17
Q9	36.00	91.00	3,244.50	132.67	137.83	174.67	804.83	8,809.00	650.83	668.67	6,264.50	DNF	42,872.00	7,992.17
Q10	39.00	72.50	5,007.17	153.17	137.50	177.17	511.00	8,129.83	680.17	702.33	1,720.33	DNF	42,925.17	8,456.50

(a) For DC10, DC100, and DC1000 (in msec)

ID	MXQ	SI	GO	SX	SX-JO	ID	MXQ	SI	GO	SX	SX-JO
D1	1,927.80	6,264.17	24,975.17	55.00	55.00	D3	2,143.60	82,539.00	32,829.17	46,827.50	2,008.83
D2	2,803.00	12,596.67	39,912.00	DNF	32,605.83	D4	2,859.20	81,575.00	32,795.00	46,820.50	1,886.83

(b) For DBLP (in msec)

Fig. 6. Query Performance (in msec)

7.1 Query Evaluation Times

Figures 6(a) (resp. 6(b)) presents the query evaluation times for the approaches on DC (resp. DBLP) dataset. Queries that Did Not Finish within 60 minutes were denoted as DNF.

Enforcement of Join Order. The SX and SX-JO columns in Figure 6 describes the effect of enforcing join order in SUCXENT++. Note that we did not enforce the join order for queries Q1, Q2, Q4, and D1 when the PathValue table appears in the translated SQL queries only once.

We made three main observations from our results as follows. First, in almost all cases the query performance improved significantly when join order is enabled. For instance, for DBLP the performance of queries D3 and D4 were improved by factors of 23 and 25, respectively. In fact, 18 out of 24 queries in Figure 6 benefited from join order enforcement. Second, the benefit of this technique increases as the dataset size increases. For instance, for the 1GB dataset the performances of Q5 to Q8 improved by 47 to 59 times. Furthermore, queries that failed to return results previously in 60 minutes (Q3, D2) were now able to return results across all benchmark datasets. Without being privy to optimizer internals, we observed from the query plans of Q3 and Q5-Q8 that the query plan trees consisted of essentially two subtrees. One depicted the plan for computing the V table (lines 03-11 in Figure 4(b)) followed by joining it to the Attribute table (Lines 16-19). The other subtree computed the V table and then returned all the attributes of V (Lines 13-14 in Figure 4(b)). Interestingly, when join order was enforced, the number of joins in the former subtree was reduced and the size of intermediate results were reduced in the later subtree. Consequently, this resulted in a better query plan. For further details on the query plans please refer to [7]. Third, the penalty of join order for most of the benchmark queries, if any, was low on all benchmark datasets. In fact, the largest penalty on the query performance due to join order enforcement was 22*ms*.

Comparison with GLOBAL-ORDER and SHARED-INLINING. Overall SX-JO outperformed both SI and GO in at least 65% of the benchmark queries with the highest observed gain factors being 880 and 1939, respectively. GO showed non-monotonic behavior for Q5-Q8 and as a result the performance of SX-JO was comparable to GO for these queries on DC1000. However, SX-JO significantly outperformed SI for Q5-Q8 (up to 30 times). Note that for DC1000, GO failed to return results for queries Q9 and Q10. Finally, for the DBLP dataset, SX-JO significantly outperformed GO and SI for D1, D3, and D4, with the highest observed gain factor 454 and 114, respectively.

Comparison with MONETDB. Our study in the context of MONETDB revealed some interesting results. First, MXQ was 11-164 and 3-74 times faster than GO and SI, respectively, for the majority of the benchmark queries. However, this performance gap was significantly reduced when it was compared against SX-JO. Our results showed that MXQ was 1.3-16 times faster than SX-JO. Surprisingly our approach was faster than MONETDB for 33% of benchmark queries! Specifically, SX-JO was faster than MXQ for Q2, Q5, and Q8 on DC10 and Q1 and Q2 on DC100. Also, for the real dataset (DBLP) SX-JO was faster than MXQ for D1, D3, and D4 with the highest observed factor being 35. Unfortunately, we could not report the results of MXQ for DC1000 because it failed to shred the document. The reason of this problem is that MXQ (Win32 builds) is currently vulnerable to the virtual memory fragmentation in Windows environment. MXQ also does not evaluate predicates applied after reverse axis in reverse document order, but in document order. Therefore, in Q8, it evaluated the second `preceding-sibling` element in document order, not in reverse document order (not in accordance to W3C XPath recommendation [13]).

8 Conclusions and Future Work

In this paper, we presented a scalable storage scheme for ordered XPATH evaluation in relational environment. The mapped SQL queries were forced to execute a "left-to-right" join order. We showed that this technique could improve query performance notably. In addition, our results showed that our proposed approach outperforms other representative *tree-unaware* approaches for the majority of the benchmark queries. Although *tree-aware* approaches were often the best in terms of query performance [1], the "join-order conscious" SUCXENT++ reduced the performance gap between tree-aware and tree-unaware approaches significantly and could outperform a state-of-the-art tree-aware approach (MONETDB) for certain benchmark queries. Importantly, unlike tree-aware approaches, our approach did not require any invasion of the database kernels to improve query performance and could easily be built on top of any off-the-shelf commercial RDBMS. As part of our future work, we are studying the "join order" phenomena encountered during our investigation. We are also exploring other non-invasive mechanisms for improving XPATH query performance on a relational backend.

References

1. P. BONCZ, T. GRUST, M. VAN KEULEN, S. MANEGOLD, J. RITTINGER, J. TEUBNER. MonetDB/XQuery: A Fast XQuery Processor Powered by a Relational Engine. *In SIGMOD* ,2006.
2. D. DEHAAN, D. TOMAN, M. P. CONSENS, M. T. OZSU. A Comprehensive XQuery to SQL Translation Using Dynamic Interval Coding. *In SIGMOD*, 2003.
3. D. FLORESCU, D. KOSSMAN. Storing and Querying XML Data using an RDBMS. *IEEE Data Engg. Bulletin*. 22(3), 1999.

4. T. Grust, J. Teubner, M. V. Keulen. Accelerating XPath Evaluation in Any RDBMS. *In ACM TODS*, 2004.
5. S. Pal, I. Cseri, O. Seeliger et al. XQuery Implementation in a Relational Database System. *In VLDB*, 2005.
6. S. Prakash, S. S. Bhowmick, S. K. Madria. Efficient Recursive XML Query Processing Using Relational Databases. *In DKE)*, 58(3), 2006.
7. B.-S Seah, K. G. Widjanarko, S. S. Bhowmick, B. Choi, E. Leonardi. Efficient Support of Ordered XPath Processing in Relational Databases. *Technical Report*, CAIS-05-2006, 2006. Available at `http://www.cais.ntu.edu.sg/~sourav/papers/OrderedXPath-TR.pdf`
8. J. Shanmugasundaram, K. Tufte et al. Relational Databases for Querying XML Documents: Limitations and Opportunities. *In VLDB*, 1999.
9. I. Tatarinov, S. Viglas, K. Beyer, et al. Storing and Querying Ordered XML Using a Relational Database System. *In SIGMOD*, 2002.
10. B. Yao, M. Tamer Özsu, N. Khandelwal. XBench: Benchmark and Performance Testing of XML DBMSs. *In ICDE*, Boston, 2004.
11. C. Zhang, J. Naughton, D. Dewitt, Q. Luo and G. Lohmann. On Supporting Containment Queries in Relational Database Systems. *In SIGMOD*, 2001.
12. DBLP XML Record. *http://dblp.uni-trier.de/xml/*.
13. XML Path Language (XPath) 2.0: W3C Proposed Recommendation 21 November 2006. *http://www.w3.org/TR/xpath20/*