Pattern tree algebras: sets or sequences?

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Abstract

XML and XQuery semantics are very sensitive to the order of the produced output. Although pattern-tree based algebraic approaches are becoming more and more popular for evaluating XML, there is no universally accepted technique which can guarantee both a correct output order and a choice of efficient alternative plans.

We address the problem using hybrid collections of trees that can be either sets or sequences or something in between. Each such collection is coupled with an *Ordering Specification* that describes how the trees are sorted (full, partial or no order). This provides us with a formal basis for developing a query plan having parts that maintain no order and parts with partial or full order.

It turns out that duplicate elimination introduces some of the same issues as order maintenance: it is expensive and a single collection type does not always provide all the flexibility required to optimize this properly. To solve this problem we associate with each hybrid collection a *Duplicate Specification* that describes the presence or absence of duplicate elements in it. We show how to extend an existing bulk tree algebra, TLC [12], to use *Ordering and Duplicate specifications* and produce correctly ordered results. We also suggest some optimizations enabled by the flexibility of our approach, and experimentally demonstrate the performance increase due to them.

1 Introduction

XML means many things to many people, and gets used in a variety of ways. The formal semantics of XML and XQuery require ordering, yet many "database-style" applications could not care less about order. This leaves the query processing engine designer in a quandary: should order be maintained, as required by the semantics, irrespective of the additional cost; or can order be ignored for performance reasons. What we would like is an engine where we pay the cost to maintain order when we need it, and do not incur this overhead when it is not necessary.

In fact, we would like even more. Even when ordered final results are required, it may not be necessary to maintain order at each intermediate step. Exploiting this flexibility, provided the required order can eventually be established (or recovered), can lead to significant performance benefits.

In algebraic terms, the question we ask is whether we are manipulating sets, which do not establish order among their elements, or manipulating sequences, which do. It is not difficult to show that just manipulating sets is not enough; we often do need to consider order in intermediate results. Yet we know that manipulating sequences is considerably more expensive, so we would prefer not to work with these if we can avoid it.

The solution we propose in this paper is to define a new generic collection type, which could be a set or a sequence or even something else. We associate with each collection an *Ordering Specification* that indicates precisely what type of order, if any, is to be maintained in this collection. We then develop an algebra for manipulating collections with ordering specifications. Using this algebra we are able to develop query plans that maintain as little order as possible during query execution while yet producing the correct query results.

Duplicates in collections are also a topic of interest, not just for XML, but for relational data as well. In relational query processing, duplicate removal is generally considered expensive, and avoided where possible even though relational algebra formally manipulates sets that do not admit duplicates. In fact, there has been considerable work towards developing multi-set relational algebras. The more complex structure of XML data raises more questions of what is equality and what is a duplicate. Therefore there is room for more options than just sets and multi-sets. It turns out that our proposal of using a generic collection type applies to this problem as well, through associating an explicit *Duplicate Specification* with each collection. We are then able to develop an algebra for manipulating such collections, and use this algebra to develop query plans in which duplicate elimination is optimized.

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```
FOR $b IN document('lib.xml')/book
FOR $a IN document('lib.xml')/article
WHERE $b/author = $a/author
  AND $b/year = 1999 AND $a/conference = 'VLDB'
RETURN <result> {$b} {$a} </result>
```

```
FOR $a IN document('lib.xml')/article
FOR $b IN document('lib.xml')/book
WHERE $b/author = $a/author
  AND $b/year = 1999 AND $a/conference = 'VLDB'
RETURN <result> {$b} {$a} </result>
```

Figure 1: Queries that would produce results ordered in a different way. The *$b - book, $a - article* switch dictates a different binding order.

The rest of the paper is organized in the following way: our discussion on ordering and duplicates in the paper starts in Section 2 by identifying the requirements set by XML and XQuery. Then we introduce our proposed solution to the problem that uses hybrid collections paired with the *Ordering Specification O-Spec* and *Duplicate Specification D-Spec* in Section 3. We then consider a set of common operators in a bulk tree-algebra (such as TLC [12]), study their behavior in relation to duplicates and order of output in Section 4.2 and show how such an approach can generate the correct results in Section 4.4. We continue by showing potential optimizations that take advantage of our features on both duplicates and output order in Section 5. In Section 6 we use TIMBER [10], a native XML system, to experimentally illustrate the benefits of using our solution and the gained performance increase.

2 Ordering & Duplicates in XML / XQuery

Before we discuss XML and XQuery ordering requirements we start with a few observations on XQuery set semantics (presence of duplicates). XQuery associates variables via the *FOR* and *LET* clauses. The *LET* clause creates a variable binding with an entire set[1] of matching XML elements (nodes) whereas the *FOR* clause creates a binding with each element (node) of a set of matching XML elements (nodes). We can see that both binding types require a duplicate-free *set* of matching XML elements to be calculated first. Hence XQuery *requires* all duplicates to be removed when creating the variable assignments to the corresponding XML parts.

XML itself incorporates semantics in the order data is specified. XML queries have to respect that and produce results based on the order of the original document (queries based on XQuery or XPath adhere to that). XQuery takes this concept even further and adds an extra implicit ordering requirement. The order of the generated output is sensitive to the order the variable binding occurred in the query. To better understand the issues with binding order an example is shown in Fig.1. Two very simple queries are shown – both perform a join between *book* and *article* elements on *author.* The output of the first is sorted on the original document order of {*book, article*} whereas the output of the second is sorted on the original document order of {*article, book*}. Notice how *article* and *book* switched places to reflect the difference in the order requirements of the two queries, although the rest of the query remained the same. In more complex scenarios with implicit ordering (including nested queries) binding order is much harder to follow correctly and efficiently.

[1] XQuery asks for sequences but for the moment we focus on the presence of duplicates (set) and discuss order further down.

1. ORDER BY clause,
   explicit, depends on value.
2. Re-establish original document order,
   implicit, required by XML .
3. Binding order of variables,
   implicit, depends on variable binding predicates.

Figure 2: Ordering Requirements for XML and XQuery

A FLWOR statement in XQuery may include an explicit *ORDERBY* clause, specifying the ordering of the output based on the value of some expression – this is similar in concept with ordering in the relational world and SQL. Note that the *ORDERBY* clause, when present, overrides document and binding order for that single-block FLWOR statement.

To facilitate our discussion in the rest of the paper, we present a summary of XQuery ordering requirements in Fig.2. An XML processing system must be able to understand and process these requirements properly. Existing XML algebras tried to produce the correct output order by using sets or sequences. Sets lose all ordering information resulting in redundant sorts throughout the query plan, whereas sequences maintain the order throughout the query plan but make it difficult to perform rewrites and need tightly bound operators that can be expensive to implement and difficult to optimize. Also, whether sets or sequences are used, semantics require no duplicates are present and so require several duplicate elimination operations to be applied through the plan. These problems motivate our current work.

3 Introducing the Hybrid Collection

In this section we introduce the core of our solution to the problem, the concept of a generic collection type with ordering and duplicate specifications. We believe that the basic principles of our collections can be incorporated into any bulk algebra, with the appropriate modifications. For our presentation we choose to follow the tree-based algebraic approach and model our collections to operate with tree structures. A tree consists of nodes, with each node mapping to an XML element or attribute. A basic assumption we make is that the nodes used are annotated with identifiers that guarantee both *uniqueness* and *document order*.

Definition 3.1 *Given a collection of trees C_T, the Duplicate Specification* D-Spec *describes how trees were determined as identical and were eliminated from the collection C_T. The value of* D-Spec *can be one of the following:*

'empty' *: Any type of duplicate tree can potentially be present in the collection C_T.*

'full tree' *: Given a tree $Qi = (Vi, Ei)$ in the collection C_T, there does not exist another tree $Qj = (Vj, Ej)$ in the collection C_T such that $Vi = Vj$ and $Ei = Ej$. $(\forall Qi \nexists Qj \in C_T, i \neq j) : [(Vi = Vj) \wedge (Ei = Ej)]$*

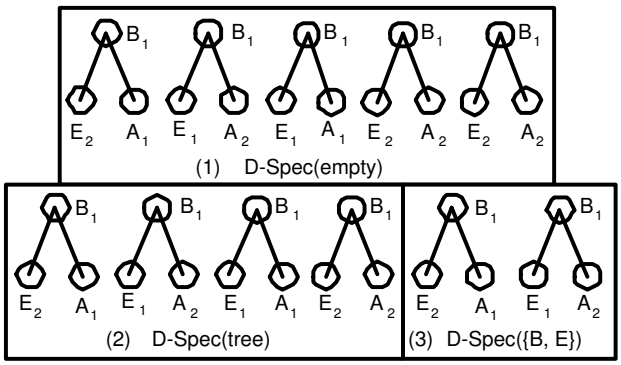


Figure 3: Collections with Duplicate Specification D-Spec.

'List of Nodes u**'** *: Given a tree* $Qi = (Vi, Ei)$ *in the collection* C_T*, with a set of nodes* $Ui \subseteq Vi$ *identified by the input List of Nodes* u*, there does not exist another tree* $Qj = (Vj, Ej)$ *in the collection* C_T*, with a set of nodes* $Uj \subseteq Vj$ *identified by the input List of Nodes* u*, such that* $Ui = Uj$*.*
$\{\forall Qi \in C_T : [(u \rightarrow Ui) \wedge (Ui \subseteq Vi)]\}\{\nexists Qj \in C_T, i \neq j : [(u \rightarrow Uj) \wedge (Uj \subseteq Vj) \wedge (Ui = Uj)]\}$

The default value for *D-Spec* is 'empty' since most operators behave gracefully with duplicates and neither add or remove them. A collection coupled with a *D-Spec* of 'empty' can potentially have any type of duplicates. Value 'tree' is mapped to duplicate elimination using deep-tree comparison between all trees in a collection. It is aimed to be used very often for describing that an arbitrary collection of trees is actually a set (sequence, if ordered). *D-Spec* also allows for a list of node references to be passed describing which nodes to be used in each tree to determine the duplicates, thus enabling support for a description of a partial duplicate elimination procedure. *D-Spec* uses a flag to specify whether the identifier (ID) or the content of a node should be used for defining duplicates.

Example 3.1 *A group of sample collections with* D-Spec *describing how duplicates were previously removed from them can be found in Fig.3. Notice the duplicates that exist in part (1), how the last tree from (1) is removed in part (2) and how multiple trees are removed in part (3) – potentially losing some information about* A *(had the trees with only* A_1 *been retained we would have lost all* A_2 *from the collection).*

As we can see, the partial-tree comparison can remove more trees than deep-tree. This option is designed to be used for optimization purposes. We can produce the correct output without it , but this would lead to a less flexible solution with redundant duplicate elimination operations with various 'tree' inputs.

The goal of *Duplicate Specification D-Spec* is to carry to succeeding operators the information of a duplicate elimination procedure that was applied earlier in a query plan, no matter whether such procedure was explicit or implicit. Given the *D-Spec* for each collection the optimizer can apply it on the plan either globally or locally. Globally by rewriting the plan and choosing where to place duplicate elimination procedures to achieve the correct result with a minimum cost. Locally by considering each operator and choosing during the physical evaluation to : a) ignore the *D-Spec* for operators that do not remove or add duplicates, b) modify the *D-Spec* appropriately for operators that remove or produce duplicates, and c) maintain the *D-Spec* for operators that require duplicate elimination but use *D-Spec* to determine that it was already applied.

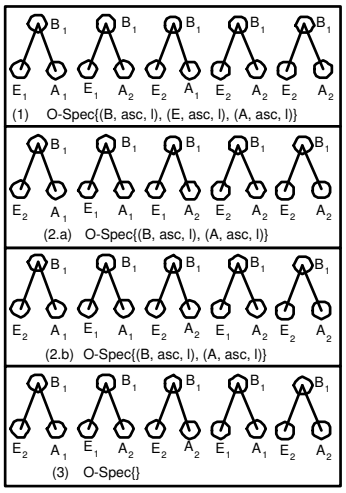


Figure 4: Collections with Ordering Specification O-Spec.

Definition 3.2 *An Ordering Item* O-Item *is the unit used when sorting a collection of trees. It consist of three parameters: i) a reference to identify the node in the tree to sort the trees by, ii) ascending ('asc') or descending ('desc') describes how to use the node information to perform the sort and iii) empty greatest ('g') or empty least ('l') describes where to place the trees without a matching node for the given input reference.*

O-Item uses a flag to refer to the identifier or content of each node. As we assumed the node identifiers used in conjunction with our collections can indicate document order for any group of nodes, we can use the node identifiers to indicate ordering based on document order. When the required order is based on a value comparison the node content can be accessed instead.

An *Ordering Item* is essentially the smallest unit that can be used to describe a sorting procedure. It matches in principle the input to a *SORT* operation. It contains the means to identify the sorting basis (what to sort on), how to use the information in the basis to perform the sort (e.g. ascending) and what to do with null entries (place them in the beginning or end of the collection). Complex sorting procedures that require multiple parameters to perform the sort can easily be described using a list of *Ordering Items*.

Example 3.2 *For example a simple sorting procedure using all* B *nodes (identifiers), sorting them on ascending order and placing all empty entries in the beginning will be described by an* O-Item *that looks like (B, asc, l). For simplicity, ascending ('asc') and empty least ('l') are the default choices and can be omitted; so (B, asc, l)→(B).*

Definition 3.3 *Given a collection of trees* C_T*, the Ordering Specification* O-Spec *specifies how the trees are sorted*

in the collection C_T. O-Spec *accepts as input a list of Ordering Items* O-Items *describing the sorting procedure that occurred on the collection. Sorting based on each* O-Item *happens in the order they are given in the input list.*

Similar in spirit with the *Duplicate Specification*, the *Ordering Specification* is used in association with a collection to describe a sorting procedure (implicit or explicit) that took place earlier in the query plan. The optimizer can use the information globally by rewriting the plan and choosing where to place sorts to achieve the correct result while using a 'quick' query plan. It can also use them locally during the physical evaluation and determine whether: a) an operator can pass it along if it does not change the order of the collection, b) modify it with a partial new sort, and c) create a completely new one when it destroys the order of the collection and/or reorders it.

Example 3.3 *In Fig.4, we can see a few ordered collections using the Ordering Specification. In part (1) we see a "fully-ordered" collection; all the nodes in every tree were used to perform the sort. A "fully-ordered" collection has one and only one way that the trees can be ordered (absolute order). In parts (2.a) and (2.b) we see the same "partially-ordered" collection; only nodes in parts of every tree were used to perform the sort. A "partially-ordered" collection can potentially have multiple ways it was ordered. Parts (2.a) and (2.b) show the same collection ordered by the same key with clearly more than one representations of the absolute tree order. In part (3) we see a collection with unspecified order (any order).*

Ordering Specification is **orthogonal** to the presence of duplicates and *Duplicate Specification*. To clarify whether a collection is an arbitrary one or it is coupled with an *Ordering* or *Duplicate Specification* we accordingly use the terms *D-collection*, *O-collection* and *OD-collection*.

An outcome of our technique is that the *Ordering Specification O-Spec* of a collection (and for that matter the *SORT* operation that produced it) is a **superset** of the potential order that can be expressed by XQuery. The output of a single block FLWOR statement in XQuery can be ordered by either the binding/document order as specified in the *FOR* clauses or the value order as specified in the *ORDERBY* clause. *O-Spec* allows for the result of a query to be sorted by the combination of binding/document and value order. In other words, despite the XQuery complex order requirements, there is no way to write a simple query that asks to "return all `books`, sorted by the document order of each `author` and the value order of each `year`". Our approach can easily handle this by specifying to access the node id (provides document order) for `author` and the node content (provides value order) for `year` in their corresponding *Ordering Items* as part of a *SORT* operation. In that sense, our approach can provide the means for more powerful ordering expressions for XML than XQuery.

4 Enhancing an Algebra

Hybrid collections can be used to enhance any algebra. We focus on the TLC [12] algebra used in the TIMBER [7] system. In this section we describe how TLC algebraic operators can be extended to handle order. We show some algebraic identities that can be generated and present the algorithm to produce the correct output order. But first we begin with some necessary background on TLC.

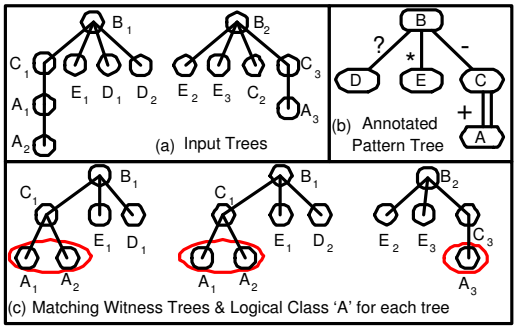


Figure 5: A sample match for an Annotated Pattern Tree.

4.1 Tree Logical Classes (TLC) for XML

All tree algebras (e.g. [3, 8]) use pattern tree match as a basic building block. A pattern tree is matched on an XML document and a collection of witness trees is produced. In previous tree algebra solutions, the witness trees had to be similar to the input pattern tree, i.e. have the same size and structure. This requirement resulted in homogeneous witness trees in an inherently heterogeneous XML world with missing and repeated sub-elements, thus requiring extra work to reconstruct the appropriate structure when needed in a query plan. TLC uses *Annotated Pattern Trees (APTs)* and *Logical Classes (LCs)* to overcome that limitation. It is not within the context of this paper to present in detail how TLC [12] works. Instead we will try to show the intuition on APTs and LCs and walk through an example with them.

Annotated Pattern Trees accept edge matching specifications that can lift the restriction of the traditional one-to-one relationship between pattern tree node and witness tree node. These specifications can be "-" (exactly one), "?" (zero or one),"+" (one or more) and "*" (zero or more). Fig.5 shows the example match for an annotated pattern tree. The figure illustrates how annotated pattern trees address heterogeneity on both dimensions (height and width) using variations of annotated edges. So A_1, A_2 and E_2, E_3 are matched into clustered siblings due to the "+" and "*" edges in the APT. On the flip side D_1, D_2 matchings will produce two witness trees for the first input tree (the second tree is let through, although there is no D matching) due to the "?" edge in the APT.

Once the pattern tree match has occurred we must have a logical method to access the matched nodes without having to reapply a pattern tree matching or navigate to them. For example, if we would like to evaluate a predicate on (some attribute of) the "A" node in Fig.5, how can we say precisely which node we mean? The solution to his problem is provided by our Logical Classes. Basically, each node in an annotated pattern tree is mapped to a set of matching nodes in *each* resulting witness tree – such set of nodes is called a *Logical Class.* For example in Fig.5, the red(gray) circle indicates how the A nodes form a logical class for each

witness tree. In TLC, every node in every tree in any intermediate result is marked as member of at least one logical class[2]. We also permit predicates on logical class membership as part of an annotated pattern tree specification, thus allowing operators late in the plan to reuse pattern tree matches computed earlier.

4.2 Operators with Duplicates and Ordering

In this section we present a group of operators that cover some core operations one would expect to be supported in an XML algebra. Every operator maps one or more hybrid collections of trees[3] to one hybrid collection of trees. The trees in a collection may be heterogeneous. Since we are using TLC, Annotated Pattern Trees (APTs) and Logical Classes (LCs) provide the means to identify nodes of interest in each operator. Some of the operators are carried over from TLC (e.g. *Project*), whereas others had to be modified to include specific ordering and duplicate aware behavior (e.g. *Select*, *Join*).

Select $S[apt, ord](C_T)$: Given a hybrid collection of trees C_T, an Annotated Pattern Tree apt and an optional ordering parameter ord: perform the matching procedure for apt in each tree of C_T and output the produced trees ordered by ord. The ordering parameter ord can be: a) 'empty', the output order is unspecified (O-Spec is empty). b) 'maintain', maintains the order (O-Spec) of the input. c) 'list-resort', output is resorted based on the list of nodes passed – the input order was destroyed. d) 'list-add', output is partially sorted based on the list of node passed – the input order is maintained and the additional parameters from ord are added to the O-Spec.

Project $P[nl](C_T)$: Given a hybrid collection of trees C_T and a list nl that identifies sets of nodes: output one tree for each tree in C_T maintaining only the nodes identified by nl. If the output is not a tree, the input tree root is also retained.

Filter $F[LC_f, p, m](C_T)$: Given an input hybrid collection of trees C_T, a filter predicate p, a mode m and a logical class LC_f: output only the trees in C_T that satisfy the predicate p for the nodes bound to LC_f. The mode m parameter is used to identify how to iterate over the set of nodes bound to LC_f, e.g. every (universal quantification – default), at least one, exactly one.

Construct $C[c](C_T)$: Given an input hybrid collection of trees C_T and an annotated construct-pattern tree c as input: output one tree for each tree in C_T modified as described in c. An annotated construct-pattern tree is an annotated pattern tree(APT), except it allows facilities for tagging, renaming, and arbitrary tree assembly. Any constructed node (e.g. a node created for a tag `<myresult>` of some `RETURN` clause) is assigned a new node identifiers with similar properties for uniqueness and document order and the identifiers of the 'regular' nodes.

Aggregate-Function $AF[fname, LC_a, newLC](C_T)$: Given an input hybrid collection of trees C_T, an aggregate function name $fname$ (count, max etc.), an LC reference LC_a to describe which nodes to apply the function on and an LC reference $newLC$ for the new node that will be created to hold the result: output one tree for each input tree, having applied the function $fname$ to the specified nodes by LC_a and place the result of the function in a new node in the tree annotated by $newLC$.

Join $J[apt, p, ord](C_l, C_r)$: Given two input hybrid collections of trees C_l and C_r, an Annotated Pattern Tree apt, a predicate p and an ordering parameter ord: output one tree for each tree from C_l that has a matching tree from C_r as described in p. The structure of the output tree matches that of the apt. The output is ordered as specified by ord: a) 'empty', the output order is unspecified and output O-Spec is empty. b) 'maintain', maintains the order of the input (left, right), the output O-Spec is the combination of the left and right input. c) 'list-resort', output is resorted based on the list of nodes passed – the input order is destroyed. d) 'list-add', output is partially sorted based on the list of nodes passed – the input order (left, right) is maintained and the additional parameters from ord are added to the combination O-Spec of the inputs.

Reorder $R[pLC, cLC, f](C_T)$: accepts an input collection C_T, two Logical Classes pLC and cLC and a function f. For each tree in C_T, identify the parent nodes pLC and the child nodes cLC then reorder cLC under each pLC as specified by the input function f.

Duplicate-Elimination $DE[dep](C_T)$: Given an input hybrid collection of trees C_T and a parameter dep: output a collection from C_T having removed identical trees compared based on dep. dep can be a) the whole tree (input 'tree') or b) a list of nodes (input dl). The output D-Spec becomes dep.

Sort $O[ol](C_T)$: Given an input hybrid collection of trees C_T a sorting basis vector ol: output collection C_T reordered as described by ol. Each entry for ol is an Ordering Item O-Item. The output O-Spec becomes ol. Sort can choose to partially order the input collection if the input O-Spec is a subset of ol.

4.3 Algebraic Identities

The power of bulk algebras is in the rewrites that rely on algebraic identities. In Table 1 we present several identities showing how our operators interact with *Sort* and *Duplicate Elimination*. We try to give the intuition on how these identities are generated.

Select and *Join* accept an optional ordering parameter that allows us to push *Sort* into them. Also, they can be set to maintain order and be swapped with *Sort*. Identities (1), (2), (3), (4) are generated because of this.

Project removes nodes from a tree and thus can create duplicates. The removed nodes might affect succeeding ordering operations. So both ordering and duplicates must be aware of the project list, hence identities (5),(6). *Construct* is somewhat similar to that because it can also remove some nodes. So identity (7) is generated.

Filter does not modify the tree structure at all. So it

[2]Base data, read directly from the database, has no such association.

[3]The input can be a single tree database.

1	$O[ol](S[any, any](.)) \Leftrightarrow S[any, ol](.))$
2	$O[ol](S[maintain](.)) \Leftrightarrow S[maintain](O[ol](.))$
3	$O[ol](J[any, any](.)) \Leftrightarrow J[any, ol](.))$
4	$O[ol](J[maintain](S_l, S_r)) \Leftrightarrow$ $J[maintain](O[ol_l](S_l), O[ol_r](S_r))$, jroot $\notin ol$
5	$DE[dl](P[nl](.)) \Leftrightarrow P[nl](DE[dl](.))$, if $dl \subseteq nl$
6	$O[ol](P[nl](.)) \Leftrightarrow P[nl](O[ol](.))$, if $ol \subseteq nl$
7	$O[ol](C[c](.)) \Leftrightarrow C[c](O[ol](.))$, if $ol \subseteq (c - cl)$, where cl the newly constructed nodes
8	$DE[any](F[any](.)) \Leftrightarrow F[any](DE[any](.))$
9	$O[any](F[any](.)) \Leftrightarrow F[any](O[any](.))$
10	$DE[any](R[any](.)) \Leftrightarrow R[any](DE[any](.))$
11	$O[any](R[any](.)) \Leftrightarrow R[any](O[any](.))$
12	$DE[tree](C[c](.)) \Leftrightarrow C[c](.))$, if c contains newly constructed nodes
13	$DE[dl](C[c](.)) \Leftrightarrow C[c](DE[al](.))$,if $dl \subseteq c$ where $al = dl - cl$ and cl the constructed nodes
14	$O[ol](DE[dep](.))) \Leftrightarrow DE[dep](O[ol](.))$, $dep \in$ O-Spec of input
15	$DE[dep](O[ol](.)) \Leftrightarrow DE[dep](.))$

Table 1: Algebraic Identities used for rewrites.

does not affect duplicates or ordering, thus (8), (9). *Reorder* does not add or remove nodes either, but modifies the tree structure by reordering it. Yet, all the tree information is retained and the modification is applied the same way to each tree; trees that were identical before reorder, become identical again. So (10) and (11) can be used.

Construct can eliminate duplicates due to the constructed nodes. The new id for the constructed node will make all trees different with each other. Identities, (12), (13) are added because of this. Similarly, *Aggregate-Function* and *Join* add their own nodes and can eliminate duplicates – they also produce similar identities to (12), (13), not shown here due to space limitations.

Duplicate-Elimination can destroy order, since it resorts the input collection by the elimination key dep to remove duplicates. Yet, if the input is already sorted by the key dep, then it is maintained. *Sort* does not create additional duplicates and it does not remove existing ones. So identities (14) and (15) are produced.

4.4 Producing the correct output order

A bulk algebra can be extended to produce the correct order using our approach. We present the sketch of an algorithm that does that by extending TLC for ordering. We call the new correct ordered algorithm TLC-C. We believe our basic principles can be adjusted to fit any XML solution. Pseudocode for the extension algorithm is shown in Fig.6. We will try to discuss the intuition behind the algorithm using an example.

Example 4.1 *Consider the query in Fig.7. This query is simplified on purpose to allow focus on how binding order is dealt with. The query asks for all* `books` *sorted by the combined document order of* `author`*,* `editor`*,* `hobby` *(of editor) and* `interest` *(of author).*

First, we present how an existing tree algebra[3] would handle such a query, the output corresponds to the left plan

```
Algorithm TLC-C
Input: a FLWOR expression   Output: a TLC-C algebra plan
Globals OPERATORS ORDERLIST

procedure SingleBlock(in FLWOR) {
Parse FLWOR, create Reductions for each Grammar Rule
For each Reduction do {
Case ForClause ::= FOR $var IN SP (Simple Path)
  *Start processing as in TLC
  create LC_f point SP.leafnode
  add LC_f to ORDERLIST
Process LET and WHERE as in TLC
Case OrderClause ::= ORDER BY SP_1, ..., SP_n Mode
  for each SP_i create aptS_i = SPtoAPT(SP_i, "-")
  for each aptS_i create a Select S[aptS_i], add to OPERATORS
  for each aptS_i create LC_i point to aptS_i.leafnode
  Create Sort[value(LC_1), ..., value(LC_n)], add to OPERATORS
Case ReturnClause ::= RETURN ReturnExpr
  *Start processing as in TLC
  if Sort was added by an OrderClause continue
  else
    Child_OP = Construct.getChild()
    for each LC_i found in ORDERLIST
      Call Survive(Child_OP, LC_1)
    Create Sort_OP = Sort[nodeid(LC_1), ..., nodeid(LC_n)]
    Construct.SetChild(Sort_OP) and Sort_OP.SetChild(Child_OP)
}}

APT function SPtoAPT(SP, mSpec)
  Return an APT (Annotated Pattern Tree) from SP (Simple Path)
    use Rel from StepAxis of SP, use mSpec for all edges
function Survive(Operator, LC_in)
  if Operator removes nodes from each tree (e.g. Project type)
    if LC_in not in Projection List
      add LC_in to Projection List
  if Operator.hasChild Call Survive(Operator.getChild(), LC_in)
procedure NestedQuery(in FLWOR)
  Process FLWOR, if (Nested) then Call SingleBlock for "inner" and "outer"
  Add a join between the outer and inner plan
    Use edge "-" for FOR, edge "*" for LET and RETURN
  Call Survive on join values and inner construct elements
  if nesting on FOR and "outer" does not have OrderClause
    Create LC_r for root of "inner" tree
    add LC_r to generated Sort of "outer" plan
    Call Survive(SortOuter.getchild(), LC_r)
```

Figure 6: Algorithm TLC-C for correct output order.

in Fig.8. The first `FOR` *clause is processed – the Simple Path*[4] *(SP) (*`doc//book`*) is converted into an Annotated Pattern Tree (APT) with "-" edges and a variable is bound pointing to the leaf (*`book` *node). Processing of subsequent* `FOR` *clauses detects the existing variables. So now each SP is merged with the existing APT. After all the* `FOR` *clauses are processed, Select1 is generated. Next the* `RETURN` *clause is processed and Project2 is generated to maintain the* `book` *before it is passed to Construct3 that generates the final output.*

The problem is an assumption that the pattern tree match will generate the appropriate order. Unfortunately that assumption is not correct. The order of the pattern tree match is that of an in-order traversal – that would produce `books` ordered by `author`, `interest`, `editor`, `hobby`, in the example above. Clearly that is not the correct output order. The TLC-C extension algorithm is designed to enhance such algebras and guarantee correctness.

Example 4.2 *The TLC-C output corresponds to the right plan in Fig.8. Each* `FOR` *clause is processed as with TLC, but now a global ORDERLIST is also generated. The list contains pointers to the Logical Classes for each leaf node in the Simple Paths of every* `FOR` *clause. For the query shown in Fig.7 ORDERLIST would be (2), (3), (5), (6), (4). Since no explicit* `ORDER BY` *clause is used, TLC-C creates*

[4] XPath expression without branching predicate.

```
FOR $b IN document(''lib.xml'')//book
FOR $a IN $b/author
FOR $e IN $b/editor
FOR $h IN $e/hobby
FOR $i IN $a/interest
RETURN $b
```

Figure 7: Simple query with not-so-simple binding order.

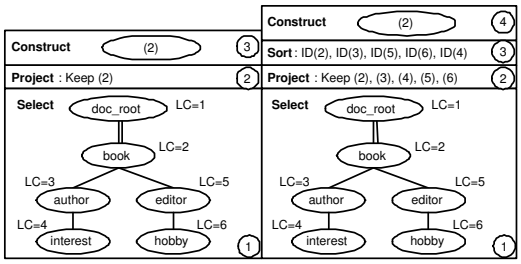


Figure 8: The TLC plan (left) vs TLC-C plan (right).

Sort3 using the information in ORDERLIST and adds it as a child to Construct4. Finally, Project2 is modified to guarantee the necessary nodes reach Sort3.

The TLC-C algorithm uses a simple concept to provide the correct order for single block FLWOR statements. Create a *Sort* operation at the end of each query that corresponds to the correct order. To achieve that it uses Logical Classes to identify which nodes participate in the order and the *Ordering Specification* to guarantee it. Also, it needs to make sure that all nodes participating in the final *Sort* are not removed from preceding operations. By default TLC-C uses O-Spec set to unordered for all operators below the final *Sort*. Only the top level *Construct* is set to maintain order – which it does by definition anyway. This way TLC-C produces almost no ordering restrictions for the plan.

For nested FLWOR queries, the single block algorithm is called for the 'inner' and 'outer' part separately. A join is used to connect the two parts. Since the 'inner' order is important the join access method is required to maintain order, essentially forcing a nested loops implementation.

5 Performance Benefits

Given the algebraic framework established above, we can develop execution plans for given query expressions. In this section, we discuss some of the optimization opportunities that become possible on account of the new algebra.

5.1 Duplicate Elimination and Efficiency

To solve the issue with no duplicates in XQuery, existing tree-based algebraic solutions [8, 3] followed the relational model and chose to operate on duplicate-free sets[5] of trees. It is very common for operations to generate duplicates in a tree algebra (e.g. a pattern tree match followed by a projection). If the set semantics were to be maintained at all times, a duplicate elimination is required after each operator is applied. For the simple query shown in Fig.9 such a plan corresponds to the left plan shown in Fig.10.

Existing tree algebra implementations use (unique) node identifiers to quickly check for duplicates. Unfortunately,

[5]Sequences are also duplicate-free. We will ignore the order for a moment and focus on duplicates, hence use sets for simplicity of presentation.

```
FOR $o IN document('auction.xml')//open_auction
WHERE count($o/bidder) > 5
RETURN <result> {$o/quantity} {$o/type} </result>
```

Figure 9: Return *open_auctions* with more than 5 *bidders*

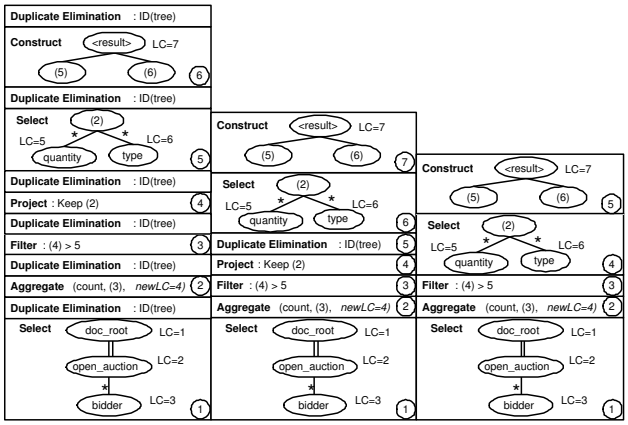


Figure 10: Minimizing Duplicate Elimination procedures.

even though the comparison operation is so cheap, Duplicate Elimination remains a blocking procedure and its cost on large sets is significant. Forcing it after every operation can cause a major performance hit.

The semantics for XQuery require the absence of duplicates, so some form of duplicate elimination is unavoidable. But, what is the minimum that can produce the same correct results as if sets were used for each operation? The complete answer to this problem can be seen in Fig.11. Here we will describe it intuitively with an example.

Example 5.1 *We use the query shown in Fig.9 and we show how to generate the middle plan in Fig.10. The algorithm iterates over the existing tree algebra plan and considers each operator. Select1 and Aggregate2 add new nodes to each tree so their output is set to D-Spec = 'tree'. Filter3 maintains the 'tree' D-Spec. Then Project4 removes some nodes and sets the D-Spec to 'empty'. A Duplicate Elimination5 procedure is necessary to remove potentially redundant trees and set the D-Spec to 'tree'. The succeeding Select6 and Construct7 do not create additional duplicates and set the output D-Spec to 'tree'.*

The produced duplicate-free result is the same as the existing algebra plan that uses sets, but now only one Duplicate Elimination is needed. The key is to change the operator input/output semantics from sets to our Hybrid Collections with *Duplicate Specification* (D-Spec). It enables the simple procedure, described in Fig. 11, to detect duplicates and eliminate them on-demand, instead of proactively.

The basic building block for XQuery is the FLWOR statement. The absence of duplicates in the final output of a FLWOR are essentially described by the FOR variable bindings. In a tree algebra, this means that only part of the output trees (the one that corresponds to the FOR bindings) needs to be used to produce the correct duplicate-free output. Existing tree algebras (including TLC) used a *Project* operation to convert into the necessary part of the tree before trying to remove duplicates. That created potential scenarios where information was projected out, only to be added later. The *Duplicate Specification* D-Spec we spec-

```
procedure FindMinimumDuplicates(in TLC-C plan)
For each Operator OP in the plan
  if OP does not modify each tree structure
    use D-Spec of input collection in the output
  if OP modifies each tree structure - adds new nodes
    use output D-Spec = 'tree'
  if OP modifies each tree structure - removes nodes
    use output D-Spec = 'empty'
    add Duplicate Elimination DE('tree')
```

Figure 11: A procedure that determines the minimum Duplicate Elimination necessary for a query.

```
procedure partialDuplicates(in TLC-C plan)
For each Operator OP in the plan
  if OP does not modify each tree structure
    use D-Spec of input collection in the output
  if OP modifies each tree structure, adds new nodes
    if D-Spec of input is 'tree' or 'empty'
      use output D-Spec = 'tree'
    if D-Spec of input is a node list (dl)
      if new node is a data node and ...
        ... connects to tree with a '-', '?'  edge
        add Logical Class of new node to dl
      set output D-Spec = dl
  if OP modifies each tree structure, removes nodes
    if D-Spec of input is 'tree' or 'empty'
      use output D-Spec = 'empty'
      add Duplicate Elimination DE('tree')
    if D-Spec of input is a node list (dl)
      if the removed nodes exist in dl
        set output D-Spec = 'empty'
        add Duplicate Elimination DE('tree')
      else set output D-Spec = dl
```

Figure 12: Taking advantage of Partial Duplicates.

ified, and in consequence the *Duplicate Elimination* operator, behave gracefully with partial lists of trees. So we constructed a procedure that further minimizes the usage of *Duplicate Eliminations* and does not require a projection. We show pseudocode for it in Fig.12. We will describe it intuitively with an example.

Example 5.2 *Consider the query in Fig.9 and the middle plan in Fig.10. The query asks for the output to be duplicate-free on* `open_auction`*. We iterate over the existing plan and consider each operator. Select1 produces output in D-Spec = (2). Aggregate2 adds a new constructed node, not data nodes – so the input D-Spec is passed to the output. Filter3 maintains the D-Spec. Project4 removes some nodes but maintains (2), so it retains D-Spec = (2). No Duplicate Elimination is required, the collection has the correct D-Spec (2) that corresponds to* `open_auction`*. The succeeding Select and Construct do not create duplicates and do not modify the D-Spec, so and the final output is correct.*

Note how the *Project* is not required for correctness any more. The right plan in Fig.10 shows the outcome of this algorithm for the query in Fig.9. *Duplicate Elimination* has been removed completely via the careful consideration of partial duplicates.

5.2 Selections and Ordering

The algorithm we used in Section 4.4 places a *Sort* operation at the end of a query plan to produce the correct output order. This placement dictates the physical implementation, which limits severely the choices for optimization. We want to overcome this problem and produce flexible plans.

The *Select* operator we described in Section 4.2 accepts an optional ordering parameter ord that can sort the produced trees according to it. There are well known techniques that can take advantage of such parameter in *Select* during the physical evaluation phase. They compute tree expressions via structural joins [2], holistic joins [1] and optimal join ordering[21, 22]. These techniques provide more efficient solutions than dictating the placement of the sorting operation at the end of the query.

```
procedure PushSortIntoSelect(in TLC-C plan)
Find the Sort at the end of the plan
Set child_OP = Sort.getChild()
While child_OP ≠ Select do
  if OP does not modify order
    swap with Sort, use proper identity
    child_OP = child_OP.getChild()
  else if child_OP modifies order
    if child_OP O-Spec is subset of Sort O-Spec
      swap with Sort, use proper identity
      child_OP = child_OP.getChild()
    else stop, operator cannot be switched
When Select found, use ordering parameter from Sort
Remove Sort from plan
```

Figure 13: Merging *Sort* and *Select.*

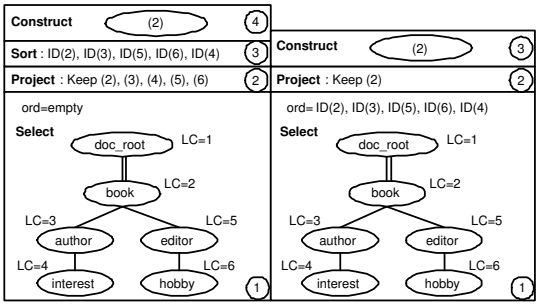


Figure 14: On the left the TLC-C plan and on the right the rewritten plan having pushed the *Sort* into the *Select.*

To take advantage of them we constructed a rewrite method that pushes the sorting operation down in a query plan using algebraic identities. This method can be applied to all selection type of queries that are based on a single block FLWOR statement without a value join. Such selection-type queries are very popular[6]. We show pseudocode for the rewrite algorithm in Fig.13. We explain it intuitively using an example.

Example 5.3 *Consider the query we used in Fig.7. In Fig.14, we can see the TLC-C plan on the left and the rewritten plan on the right. The rewrite first swaps Sort3 with Project2 using identity (6) (from Section 4.3). Then it merges Sort3 into Select1 using identity (1). The ordering parameter ord specifies the order for the query now. As a side effect, the extra nodes from Project2 can be removed.*

This rewrite should always be applied on single block selection queries because it cannot lead to a 'bad' plan. The selectivity of such query is determined by the original selection and the trees produced when matching the pattern tree of the selection to the database. The worst case scenario would be for the optimizer to not incorporate sorting into the pattern tree match and apply it afterwards. Since the selectivity is the same, we will do no worse than the TLC-C plan.

[6]For example, as we will see in the experimental section, 15 out of 20 XMark queries fit in this category.

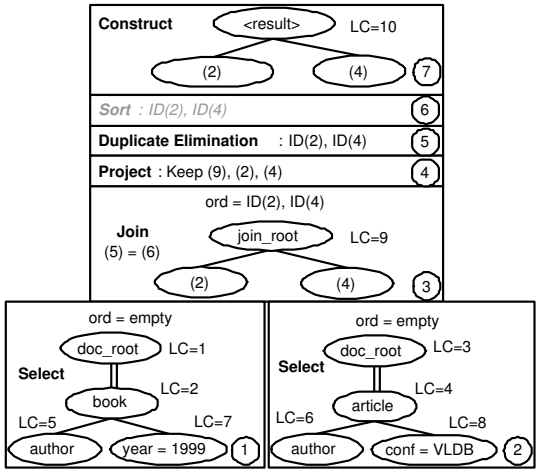


Figure 15: Merging *Sort* and *Join.* The TLC-C plan includes the gray *Sort6* operator instead of the ord in *Join3.*

Very often selection queries can include value joins and with the proposed rewrite we may miss some optimization opportunities. For this purpose, we designed the *Join* operator to accept an ordering parameter ord similar in concept with *Select.* It is applied when the join is performed and the output is ordered by it. So we can use a similar algorithm to push the *Sort* operation into a *Join.* The pseudocode is omitted both for presentation simplicity and space limitations. Instead we will show an intuitive example and discuss issues that arise.

Example 5.4 *Consider the top query from Fig.1. Fig.15 shows the plan for this query. The TLC-C plan, before the rewrite, would include the gray Sort6 operation. The Sort6 is swapped with DE5 using identity (14) and with Project4 using identity (6). Then merged to Join3 using identity (3). The ord for Join3 describes the query order now.*

Yet, this is not the only alternative. The rewrite can instead use identity (4) and push the *Sort* further down using partial ordering. That could produce a plan where *Join* maintains the order (with *Join3*-ord = maintain(left, right)) and the *Selects* specify the document order (with *Select1*-ord = ID(2) and *Select2*-ord = ID(4)). Other choices include using value ordering for a more efficient merge join algorithm. *Join* can establish binding order (with *Join3*-ord = [ID(2), ID(4)]) and the *Selects* provide the input sorted on join value (with *Select1*-ord = value(2) and *Select2*-ord = value(4)). Or a mix of value and document order (with *Join3*-ord = [maintain(left), ID(4)], *Select1*-ord = ID(2) and *Select2*-ord = value(4)). The supported partial order by the *Ordering Specification* provide many possibilities.

Pushing *Sort* to *Select* was a much simpler rewrite than *Sort* to *Join.* The difference is due to the selectivity estimation for the query. Previously, only the selection (essentially the pattern tree match) provided the selectivity for the query. Now the optimizer has to carefully consider the cost for the two *Selects* and the *Join* before making a choice.

5.3 Nested queries

Nested FLWOR statements, as we described in Section 4.4, are treated as two single block queries – one for 'inner' and one for 'outer'. A *Sort* is used on both to establish proper order. A *Join* is used to connect the produced plans for 'inner' and 'outer' part. Since the order of the 'inner' plan is important the connecting *Join* is set to maintain order. This choice dictates the physical implementation for sorting and essentially forces a nested-loops join to be used.

```
FOR $b IN document('lib.xml')/book
LET $k := FOR $a IN document('lib.xml')/article
  WHERE $b/author = $a/author AND $a/conf = 'VLDB'
  RETURN $a
WHERE $b/year = 1999
RETURN <result> {$b} {$k} </result>
```

Figure 16: Nested FLWOR statement.

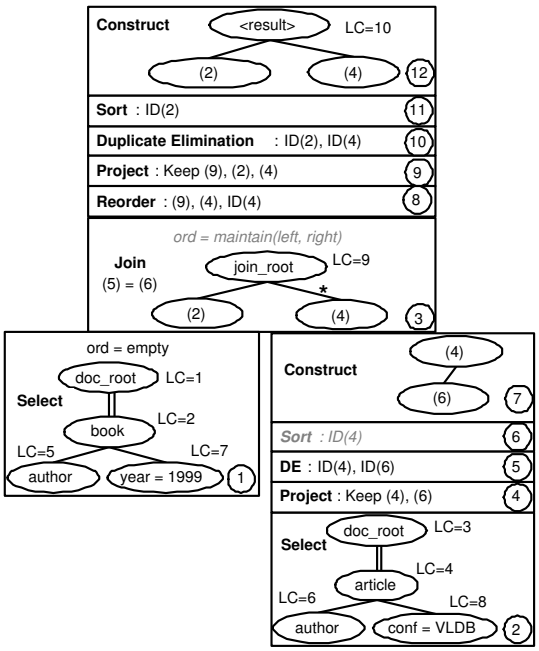


Figure 17: Reorder used in a nested FLWOR. The TLC-C plan would include the gray*Sort6* operator and the ord parameter of *Join3* instead of *Reorder8.*

When the nesting occurs in FOR we can overcome this problem by pulling the 'inner' *Sort* in the 'outer' part and over the *Join*, using identity (4) from Section 4.3. Now we can apply the rewrite we described earlier with pushing *Sort* to *Join.* Yet, this does not apply to the more popular choices for nested FLWOR statements – nesting in the LET/RETURN clauses. For each LET/RETURN clause, the *Join* needs to cluster the matching trees of the 'inner' plan together, hence identity (4) cannot be applied. There is no 'outer' *Sort* operation that can describe the 'inner' order properly. So we constructed a rewrite that uses *Reorder.*

The *Reorder* operator processes one tree at a time, resorting sub-trees as specified by its input parameters. The rewrite, that uses *Reorder* to provide alternative plans for nested FLWOR statements, has a very complex algorithm. The complexity is due to the variety and complexity of the nested queries it can handle. The algorithm is, for the most part, mundane and very specific to our system. Instead of presenting it in detail, we will show an example that intuitively demonstrates its behavior.

Example 5.5 *Consider the FLWOR statement nested on LET shown in Fig.16. The TLC-C plan for this query is*

shown in Fig.17 when the grayed out Sort6 operator and Join3-ord parameter are used instead of Reorder8. To produce the TLC-C plan, the 'inner' and 'outer' parts of the query are processed separately and a Sort is generated for each one. Then Join3 is used to connect them. Notice how the APT for Join3 uses the '' annotated edge to capture the LET semantics and how the 'inner' join node (LC=6) is added to the Project4, Duplicate Elimination5 and Construct7 operators to properly reach the connecting join. The rewrite examines the Sort6 operator of the 'inner' plan. Then it pulls it into the 'outer' plan and converts it to the appropriate Reorder8 operator. It also removes the order maintenance restriction from Join3 and enables the order of the 'inner' query to be anything.*

The basic principle of the 'Reorder' rewrite is to pull the 'inner' *Sort* to the 'outer' part of the query. Then use *Reorder* to describe it and remove the order maintaining restriction from the connecting *Join.* Once that restriction is lifted from the *Join* we can produce a series of alternative plans following the techniques presented earlier (push-Sort-in-Join). The *Reorder* operator is non blocking (processes one tree at a time), hence it is cheaper than the 'inner' *Sort.* When used in conjunction with a join procedure, it lifts the order maintaining restrictions. So it is expected to provide a big performance increase against a blocking *Sort* followed by a nested loops *Join.*

6 Experimental Evaluation

The experiments were executed on the TIMBER [10] native XML database system. For our dataset we used the XMark [13] generated documents. Factor 1 produces an XML document that occupies approximately 707MB (472MB for data plus 241MB for indices) when stored in the database. Experiments were executed on a Pentium III-M 866MhZ machine with a regular IDE hard disk and 512MB of RAM. The database was set to use an 128MB buffer pool. All numbers reported are the average of the query execution time over five executions[7]. XQuery queries were translated to TLC-C plans using our algorithm as specified in Section 4.4. The plans utilize our algebraic operators, with no structural rewriting or cost-based optimization performed. We used an index on element tag name for all the queries, which returns the node identifiers given a tag name. On all queries that had a condition on content we used a value index, which returns the node ids given a content value. We did not use value join indices.

We executed a series of queries, those described in the XMark benchmark as well as our own. We summarize our results in Table 2. We refer to XMark queries as x13, x8 etc. Since XMark does not have single block join queries, we constructed two such queries (q1, q2) and include their results. There is nothing special about them, but due to space limitations we will not describe them here.

The results for our tests are summarized in Table 2. Our tests focus on the suggested rewrites on duplicates and ordering we presented in Section 5. The TLC-C column uses the correct plan produced as in Section 4.4. The TLC-D column uses plans produced by applying only the duplicate related rewrites (no ordering consideration). Similarly TLC-O column is for only the ordering related rewrites. Finally, TLC-OD column shows results when using both ordering and duplicate rewrites. We did not want to test TLC-C against another algebraic solution because it is not clear who address ordering properly[8].

Efficiency and Duplicates: In column TLC-D, we show the performance gained with the duplicate related rewrites described in Section 5.1. The rewrites can be applied to any type of query and successfully minimize the presence of *Duplicate Eliminations* in the plan. We always expect some performance increase over TLC-C when using this rewrite. For single block selections, we expect the performance increase to depend on the query selectivity. When many results are produced removing the blocking operation can lead to a higher performance increase – e.g. the speedup of x19 vs. x17. For single block joins and for nested queries, other factors usually dominate the cost, so the performance increase can be lower. For example, in query q2 the cost is dominated by the data materialization needed for the join and the speedup is relatively low. Similar behavior is seen in nested queries, like x8.

'Push Sort in Select': We tested the efficiency of our rewrite that pushes *Sorts* into *Selects*, as described in Section 5.2. The rewrite applies only to single block selection queries. Results for such queries are shown in column TLC-O for the first group of queries (x1-x20) in Table 2. Selection queries are popular in XML (the majority of the XMark queries fit the category). We expect to always see a performance increase with our rewrite on such queries. This happens because the selectivity of the query is mostly given by the *Select* operator. So when we merge sorting into it, we create a controlled environment for the optimizer to use well known techniques that efficiently perform the pattern tree match. The overall speedup depends on the number of results in each query. A query that produces many results is hurt more by a blocking *Sort* and benefits more from a semi/fully pipelined pattern tree match physical evaluation. So the performance increase is higher for such queries – e.g. x19 shows a high speedup.

'Push Sort in Join': Pushing *Sort* into a *Join* applies to single block join queries. Results for such queries are shown in column TLC-O for the second group of queries (q1-q2). The difference between this rewrite and the 'push-in-Select' is the variety of produced alternative plans. This causes the selectivity estimation to be a bit trickier, since it has to use information for the value join and the selection operations. TLC-C by default enables unordered results up to the final *Sort* operation. So the default *Join* could have been planned with sort-merge before performing the rewrite. In that case, the performance increase depends on

[7] The highest and the lowest values were removed and then the average was computed

[8] We believe ignoring proper order by other algebras and hence missing some sort operations can be an unfair performance advantage against TLC-C. A comparison of TLC against other algebras is shown in [12].

	TLC-C	TLC-D	TLC-O	TLC-OD
x1	0.177	0.148	0.112	0.092
x2	2.163	1.260	1.142	0.737
x3	7.660	5.003	4.792	2.826
x4	1.064	0.790	0.688	0.493
x5	0.603	0.469	0.420	0.313
x6	0.390	0.259	0.248	0.164
x7	1.738	1.083	1.021	0.641
x13	0.951	0.668	0.621	0.417
x14	8.014	6.384	4.122	2.830
x15	3.440	2.382	2.176	1.503
x16	4.114	3.158	2.503	1.967
x17	2.751	1.833	1.736	0.865
x18	0.390	0.266	0.274	0.177
x19	5.541	3.478	3.308	1.485
x20	2.340	1.584	1.807	1.020
q1	9.074	8.443	5.044	3.992
q2	14.079	12.633	13.763	11.564
x8	123.208	114.648	11.138	9.649
x9	139.945	117.860	12.411	10.453
x10	>1800	>1800	168.231	160.372
x11	155.148	137.014	16.390	13.443
x12	70.167	61.966	7.412	6.141

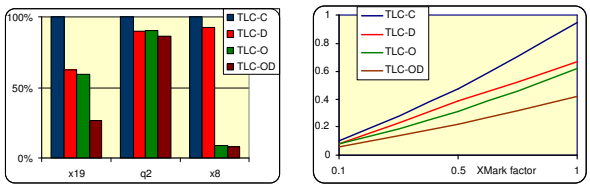
Table 2: Execution time for XMark queries. The queries are separated into three groups, a) single block selections (x1-x20), b) single block value join (q1,q2) and c) nested FLWOR (x8-x12).

the selectivity of the join operation. If the Join has two 'big' input collections and outputs a 'small' one, the speedup of the rewrite will be low – the plan close to the 'optimal' was already selected. In the queries shown in Table 2 , q2 is such a query and the speedup is relatively low. On the flip side, q1 generates a bigger number of results and the speedup is higher (2x).

'Nested Queries': Nested FLWOR statements benefits from the 'Reorder' rewrite we described in Section 5.3. Results for such queries are shown in column TLC-O for the third group of queries (x8-x12). The rewrite removes the blocking 'inner' sorting procedure and lifts the order maintaining requirement for the connecting join. Aside from enabling a more efficient join algorithm than nested loops, the rewrite enables the 'push-in-Join' and 'push-in-Select' to be fired as well. As expected, the rewrite creates a big performance increase. For the nested queries of XMark, the speedup is around an order of magnitude – e.g x8.

TLC-OD: Of course both duplicate and ordering rewrites can be used in tandem to produce even better plans. We apply the duplicate rewrite first and then the corresponding ordering one, for each query in Table 2 – results are summarized in column TLC-OD. To better summarize our observations we show a graph for a few of the queries in Fig. 18(a). The figure shows the performance fraction of each rewrite against the original TLC-C plan. In single block selection type queries (x19) both TLC-D and TLC-O contribute by removing the blocking factor of *DE* and *Sort*. For queries where other factors dominate the cost, like join q2, the speedup is relatively small. For nested queries, like x8, removing duplicates does not make much of a difference, yet, the ordering rewrite provides a big boost.

Scalability: We also present a small graph in Fig.18(b) to show how larger datasets affect our techniques. In the figure we show a simple single block selection type query (x13) and the execution time of TLC-C, TLC-D, TLC-O and TLC-OD on various document sizes. Both *Sort*



(a) TLC-OD breakdown (b) Scalability, query x13

Figure 18: Optimizing TLC-C.

and *Duplicate Elimination* are blocking operations and can cause poor performance on big collections with many trees. Larger documents will generate results that use such collections, so we expect to see higher speedup for them. This is verified in the figure by the increasing gap between the TLC-C (top) and the other curves.

7 Related Work

In the relational world, smart sort placement has been considered an interesting problem for a long time (see [5, 15]). A paper that shares similar principles with our approach is Interesting orders [18]. Their technique assumes QGM (a dataflow graph) is used to query a relational system. They use ordering properties to annotate each box in QGM and then use graph algorithms to minimize the sorts used. But they do not seem to support partial ordering or consider duplicates like we do. Also they use sequences, whereas we use the more flexible arbitrary hybrid collections. Furthermore, it is not clear how their technique can be transferred to XML. Overall, XML poses some ordering requirements that are foreign to the relational model.

There has been some work for mapping XML to a relational system [4, 16, 19]. These solutions try to address the ordering problem converting it to SQL ORDERBY clauses. This can lead to correct results for ordering on value, but there is no comprehensive study on how the binding/document order requirements can be expressed. Also, there is no discussion on optimization possibilities for ordering and duplicates.

Native navigational-based [17] approaches iterate over data nodes, thus are able to follow the XQuery iteration model step by step. Using this model one can produce the correct output order. Following this general approach, the authors in [6] present a very thorough study for ordering in XML and use a theoretical analysis to capture the ordering semantics. They do try to touch on some optimizations for navigational systems. Yet, the instance at-a-time operation leaves a lot to be desired with regards to performance and scalability of such solutions.

Native algebraic-based [10, 11, 14] implementations, and both the node [9, 20] and tree algebras [3, 8, 12] used as their basis, have the benefit of a more flexible optimization framework. But they have their own share of problems with XML order. They try to produce the correct output by using sets or sequences of trees. Sets lose all ordering information, so the correct result cannot be guaranteed at all times. Also, sets can create performance problems because redundant sorts will be used whenever something

needs to be ordered. Sequences can maintain the order throughout the query plan, but they are lacking a careful consideration of XQuery ordering requirements (especially binding order). A pattern tree match will not produce the correct order as we saw in Section 4.4. Performance-wise, sequences need tightly bound operators that reduce flexibility and have to consider the entire plan before producing a rewrite (making local optimization difficult). Finally, both sets and sequences assume no duplicates are present and required several duplicate elimination operations to be applied through the plan. The solution we proposed addresses all these difficulties and also provides a good optimization framework.

8 Final Words

Ordering in XML query processing is a complex, yet important procedure, with a complex specification and significant performance ramifications. We presented a solution that uses hybrid collections annotated with an *Ordering Specification* as the means for a correct and flexible solution. Paired with ordering is the presence of duplicates, which we address in a similar manner adding a *Duplicate Specification* to our collections. We showed how an XML tree algebra can be extended to incorporate our hybrid collections producing the correct results. We presented several algebraic optimizations that take advantage of hybrid collections and experimentally demonstrated the performance increase they engered.

While the presentation in this paper was of necessity focussed on a specific algebra, the concept of a hybrid collection is applicable much more generally. It can certainly be used in conjunction with any other XML algebra. In fact, hybrid collections may turn out to be useful even beyond XML. Figuring out where and how, is left to future work.

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