Efficient Indexing and Querying in XML Databases

Ankita Atrey
ankita.atrey2012@vit.ac.in
School of Computing Science and Engineering,
VIT University, Vellore, India

Akhil Arora
aarora@cse.iitk.ac.in
Dept. of Computer Science and Engineering,
Indian Institute of Technology, Kanpur, India

Vinay Rawal
rawalvin@cse.iitk.ac.in
Dept. of Computer Science and Engineering,
Indian Institute of Technology, Kanpur, India

Arnab Bhattacharya
arnabb@iitk.ac.in
Dept. of Computer Science and Engineering,
Indian Institute of Technology, Kanpur, India

Abstract

Optimizing XML queries is an intensively studied problem in the field of databases of late. The topic has a host of applications, viz., web-scale XML and keyword search. In this paper, we address the problem of efficient execution of XML path queries (commonly known as XPath queries), branch queries and wild-card queries. Our index structure assists in fast identification of child-parent as well as ancestor-descendant relationship, thus increasing the efficiency of XPath query execution. Both XML data and queries possess an inherent tree structure and, thus, fast child-parent lookup is a necessity to improve performance. We propose a holistic hybrid index structure that combines the Extended Dewey labeling scheme with the CTree index structure to leverage advantages of both the mechanisms. Our index structure is capable of catering to all the queries (single path, branch and wild-card queries), with equal or better performance metrics when compared to the state-of-the-art.

Keywords: XML Indexing; XPath Queries; Wild-card queries; Numbering schemes;

1 Motivation

Extensible Markup Language (XML) has always been one of the standard ways of data representation. Generally, XML is used for data transport over the web, e.g., in web services. The growth of the web has been exponential over the past few years and, thus, querying and storing of XML data efficiently is of prime importance. The use of XML databases is attractive and abundant owing to its platform independence. The bibliography database, that is the DBLP database (www.dblp.org/) indexes thousands of research papers that are published every year. To give an estimate, the size of the DBLP database is in millions at present.

XML and related tools have gained popularity over the past decade especially when it comes to web services and applications. Hundreds of XML-based languages have been developed, including RSS, Atom, SOAP, and XHTML. Both XML data and queries possess an inherent tree structure. Thus, the most intuitive way to query XML data is to incorporate the use of regular expressions. For example, suppose we want to list the names of all the authors who have published a paper in a conference, from the DBLP database. The query can be framed as //conf/*/author. Figure 1 shows a sample DBLP database, where the root node is bib containing various conf child nodes; similarly, other relationships can be inferred. The naïve way of executing such a query would be to explore all the paths in the XML tree from root to the author, which would result in exploring the whole tree making the solution highly inefficient. This area has gained active research interest over the past decade and efficient algorithms have been devised to solve such queries.

Efficient XPath query execution finds direct applications in querying databases like the DBLP database. There are a lot of complex queries, for example branching and wild-card queries, which are
explained in Section 3.3. These queries require special attention as provided in many of the previous works: CTree index structure [20, 21], TwigStack [1] and TJFast [14].

In this paper, we address the problem of optimizing these complex queries which are inefficient to solve with the help of the current state of the art techniques. We propose a hybrid index structure combining novel labeling and hierarchical schemes to achieve the same. The basic idea is to traverse the XML tree efficiently and search for various patterns of interest. Our hybrid indexing scheme combines the numbering scheme approaches (extended Dewey labeling scheme) and the properties of hierarchical structures, viz., CTree.

The rest of the paper is organized as follows. In Section 2, we provide some necessary background to XML Indexing and throw light on some of the significant and novel contributions in the past. In Section 3, we describe in detail our algorithms for index construction and querying. Section 4 establishes the efficiency and efficacy of our approach by performing experimentation on real-world datasets. Finally, we summarize our work and discuss some future work in Section 5.

2 Background and Related Work

The significant growth of XML data over the web has encouraged research in query optimization and efficient indexing of these databases. Work in this area started with research on numbering and encoding schemes [19, 4] and path (single and branch) queries [12, 8, 6, 5, 20, 21, 9]. Then came along twig-pattern queries imparting a new perspective to the field [1, 14, 10]. The introduction of novel and complex queries led to wild-card queries [2, 16] and keyword-based queries [3, 7, 15, 17, 18, 11].

As mentioned in Section 1, let the query be //conf/*/author. In 2001, Li et al. [12] proposed an efficient way to execute such queries by decomposing the complex regular path expressions into several simple path expressions. The result of these simple path expressions are joined together to construct the final result. A possible decomposition for the above mentioned example query could be, //conf and //author, where the former means finding all the conf nodes and the latter means finding all the author nodes in the database. The join step is then to find the subset of the author node set that are descendants of the set represented by the conf nodes. Ives et al. [9] have taken the path expression query to a newer dimension by introducing an efficient index structure for streaming XML data. Similar to XPath queries, research has also been done in the area of design of simple query languages [3, 7, 18, 11, 15, 13] for XML databases that are appropriate for a na"ive user. The above problem has also gained importance in the field, due to its impact on the common users.

2.1 Numbering Schemes

Researchers have introduced many different numbering/encoding schemes that help in efficient identification of child-parent and ancestor-descendant relationship. Dietz [4] introduced a numbering scheme for maintaining ordered linked lists, which further were used in XML trees to label the nodes. According to this approach each node is labeled with a 2-tuple <preorder, postorder>:

\[ \text{pre}(x) < \text{pre}(y) \] \& \[ \text{post}(x) > \text{post}(y) \] \iff \text{ancestor}(x, y) \]

where \text{ancestor}(x, y) denotes that \( x \) is an ancestor of \( y \), and \text{pre}(x) and \text{post}(y) signify the preorder and postorder of each node respectively. Figure 2 shows a sample XML database with the nodes labeled by the
above mentioned numbering scheme. It is obvious from Figure 2 that \textit{ancestor}(A, B) as (2 \textless 4) \& (3 \textgreater 2), whereas \(\neg\textit{ancestor}(A, C)\) as (2 \textless 5) but (3 \(\not\textless\) 7).

Li et al. [12] proposed a similar numbering scheme which associates a pair of numbers \(\langle\text{order, size}\rangle\) with each node, where \textit{order} is an extended preorder and \textit{size} is the range of descendants. Extended preorder of a node covers any number greater than the actual number of that node in the preorder traversal of the tree. Assigning labels using extended preorder instead of preorder ensures the dynamic growth of the database. The ancestor-descendant relationship can be identified as follows:

\[
\text{order}(x) < \text{order}(y) \leq \text{order}(x) + \text{size}(x) \implies \text{ancestor}(x, y)
\]

where \textit{ancestor}(x, y) denotes that \(x\) is an ancestor of \(y\). Figure 3 shows a sample XML database with the nodes labeled by the above mentioned numbering scheme. It is obvious from Figure 3 that \textit{ancestor}(A, B) since 10 \textless 17 \(\leq\) (10 + 30), whereas \(\neg\textit{ancestor}(A, C)\) since 10 \textless 41 \(\not\leq\) (10 + 30).

Hu et al. [8] proposed a Dewey number scheme, which associates each node with a pair \(\langle\text{level, c}\rangle\), where \textit{level} has the usual meaning and \textit{c} is in the form \(c_1 : c_2 : \ldots : c_k\), where \(k\) is the \textit{level} of the node. The label of a node at level \(k\) is \(\langle k, c_1 : c_2 : \ldots : c_{k-1} : c_{\text{child}} \rangle\), where \(c_{\text{child}} = i\) if the node is \(i^{th}\) child of its parent. The ancestor-descendant relationship can be identified as follows:

\[
\text{level}(x) < \text{level}(y) \& \text{prefix}(\langle c(x), c(y) \rangle) \implies \text{ancestor}(x, y)
\]

where \textit{ancestor}(x, y) denotes that \(x\) is an ancestor of \(y\) and \textit{prefix}(x, y) denotes that \(x\) is a prefix of \(y\). Figure 4 shows a sample XML database with the nodes labeled by the above mentioned numbering scheme. It is obvious from Figure 4 that \textit{ancestor}(A, B) as (2 \textless 3) \& \textit{prefix}(1 : 1, 1 : 2), whereas \(\neg\textit{ancestor}(A, C)\) as (2 \textless 3) but \(\neg\textit{prefix}(1 : 1, 1 : 2)\).

2.2 Indexing Schemes

The literature also witnessed a few index structures which didn’t use any numbering schemes to label the nodes. Goldman et al. [5] proposed an index structure called Path summary tree, which facilitated fast execution of single path regular expression queries. Each node in a path summary tree is actually a set of nodes containing their labels, which is formed by grouping all the nodes of the original XML tree that share a common prefix path. The particular scheme is advantageous in a way that, the answer set of a query is pre-computed during the construction of the index and stored in the node denoted by the terminating label of the path. Zou et al. [20, 21] proposed a new index structure called CTree, which was a modified version of the path summary tree, and facilitated efficient execution of both single path and branch regular expression queries. Each node in the CTree is a set,
Figure 5: A sample DBLP XML tree.

Figure 6: The path summary tree and CTree of the XML tree containing the index of its parent (as in the original XML tree) in the CTree parent node, which helps in maintaining the child-parent information unlike path summary tree.

Figure 5 shows an example DBLP database and Figure 6 shows the corresponding path summary tree and CTree. The DBLP database is a heterogeneous database, that is nodes having the same label may contain different number of children, which causes problems while executing branch queries in the path summary tree. For example, the node labeled article in Figure 5, that is node numbers \{2, 13, 16\} contain different number of children. Suppose the query /dblp/article/title is fired, the expected answer set should consist of node numbers \{3, 14, 17\}, which is evident in the corresponding subfigures’ nodes named 2 : title of Figure 6. The performance of both the index structures is same for single path queries. If the query fired is /dblp/article\{title and year\}, which means find all the articles under dblp which contain both a title and an year field, the expected answer set should contain the nodes \{2, 16\}. The path summary tree in figure 6 will not be able to utilize the precomputed node labels, as the 1 : article node is not aware of the information present in its children nodes. Therefore, it can only tell that node numbers \{2, 13, 16\} are the candidate answers. In CTree, on the other hand, the children of the 1 : article node contain information about the parent labels. As seen in figure 6, the answer set can be computed by taking the intersection of the node labels 2 : title and 4 : year.

A lot of index structures were developed that used the numbering schemes as well, catering to even more complex queries. After single path and branch queries another set of queries came into picture, called twig-pattern and wild-card queries. Given a twig pattern, all the occurrences of this twig pattern need to be searched against the XML database. The naïve approach suggests decomposition of the given twig pattern into binary structural relationships and perform matching for each of these separately which can be stitched together to obtain the final result. The disadvantage of the naïve approach is that the size of intermediate results [1] can be very large. Bruno et al. proposed a novel twig join algorithm called TwigStack [1] which is motivated by another twig join algorithm named as PathStack. It guarantees the absence of intermediate results, thereby gaining on efficiency. Linked stacks are used as a data structure in this approach.

Lu et al. [14] proposed a new labeling scheme called Extended Dewey encoding which is an effective numbering scheme when compared to other schemes and holds enough information associated with a label. Previous techniques like PathStack and TwigStack algorithms used region encoding numbering scheme that possesses very less information within a single label. Thus a new approach, based on the extended Dewey numbering scheme, was proposed called the TJFast [14] algorithm. When compared to the previous techniques, TJFast accesses only the leaf nodes, therefore reducing the number of accesses. When compared to TwigStack this approach has a broader optimal query set, for which the size of intermediate results are zero. This approach also leverages fewer disk accesses pertaining to the access of only leaf nodes. The motivation behind using the Extended Dewey scheme lies in the amount of information embedded with the labels. The structural information can be captured by means of only the labels.

As an extension to the above techniques which involve a two-step twig-join procedure, Jiang et al. [10], introduced a novel holistic one-phase twig join procedure. This work led to a lot of new avenues in this field, as this took the work even a step further. Chan
et al. [2] present a technique to minimize the wildcard steps of the XPath query. A layer axis was proposed which is used to rewrite the wildcard steps from the given twig pattern. Rewriting for both branching as well as non-branching nodes are included in this approach.

Wu et. al. [16] proposed an approach for the optimization of XML twig-pattern queries with wildcards. A new AD-dis axis is given in this approach which is basically equal to rewriting the query without any wildcard nodes. Relationships between the adjacent nodes in the twig-pattern like parent-child edge or an ancestor-descendant edges, twig-pattern matching with OR predicate and NOT predicate are some of the existing works. Wildcards are used in various queries where some elements do not matter semantically or are unknown. AD-dis axis, which has been proposed in this paper is an improvement over the AD-edge, assigning a distance called range represented as //range to each adjacency edge. This facilitates efficient and easy rewriting of the wildcard queries.

3 Approach

Majority of our ideas are formed on the lines of CTree [20, 21], which is an elegant solution for efficiently solving the XPath queries and TJFast [14], which is a holistic twig-join algorithm. We propose an alternate index structure, the “CDTree” that aims at addressing the same problem by combining numbering schemes with the tree structure. We believe that no index structure in the literature exists which utilizes both the numbering scheme approaches and the properties of the CTree [20, 21]. Prior to describing our index structure in detail, we would throw light on some of the important and basic concepts that will act as foundation stones for understanding the solution.

3.1 Meaningful Dewey Code (MDC)

There has been a lot of research to devise novel numbering/encoding schemes for labeling the XML tree. We have covered all the major work in this area in Section 2.1. We revisit one of the work that is an extension to the Dewey code [8], and is called the Meaningful Dewey code. This work was carried out by Li et al. [11] in an altogether different domain, i.e., the keyword search. We aim at using the same scheme for labeling our XML tree to produce a structure equivalent to the CTree [20, 21]. The numbering of the nodes is done according to the formula mentioned in the Equations 1 and 2.

\[
O_n = \begin{cases} 
    k & \text{if } n \text{ is the first child of parent}(n) \\
    O_{\text{presib}(n)} + k - O_{\text{presib}(n)} \% m & \text{else if } O_{\text{presib}(n)} \% m < k \\
    O_{\text{presib}(n)} + m + k - O_{\text{presib}(n)} \% m & \text{otherwise}
\end{cases}
\]

\[
C_n = \begin{cases} 
    0 & \text{if } n \text{ is the root node} \\
    C_{\text{parent}(n)} \cdot O_n & \text{otherwise}
\end{cases}
\]

The MDC assigned to the nodes in the XML document tree are very useful in finding the ancestor-descendant or child-parent relationship efficiently and they also help in finding the Least Common Ancestor (LCA) of two nodes. With the help of this numbering scheme we can build an index structure which can be used to solve regular path expression queries. The properties of the MDC are explained in detail as follows:

1. Node X is an ancestor of node Y iff \( C_X \) is a prefix of \( C_Y \). X is the parent of Y iff \( C_X \) is a prefix of \( C_Y \) and \( |C_X| = |C_Y| - 1 \), where \( |C_N| \) denotes the length of \( C_N \), i.e., the depth of node \( N \) in the XML document tree.

2. Node X follows (or precedes) node Y iff \( C_X \) is greater (or smaller) than \( C_Y \) in lexicographical order.

3. Node Z is the LCA(X, Y) iff \( C_Z \) is equal to the longest common prefix of \( C_X \) and \( C_Y \).

4. Given the MDC of a node, we can deduce its ancestors’ MDCs and elementary types based on the numbering scheme.

We will illustrate an example for a better understanding of the properties mentioned above from the sample presented in Figure 7. The node \( \text{conf} \) numbered 0 is an ancestor of the node \( \text{author} \) numbered 0.6.1, as 0 is the prefix of 0.6.1. Similarly \( \text{conf} \) numbered 0 is the parent of \( \text{paper} \) numbered 0.6 as 0 is the prefix of 0.6 and \( |0.6| = 2 \), \( |0| = 1 \) thus \( |0.6| - |0| = 1 \) which is according to the property 1 mentioned above.

The LCA of the nodes \( \text{title} \) numbered 0.2.0 and \( \text{author} \) numbered 0.6.4 is the node \( \text{conf} \) numbered 0, since the longest common prefix of the two nodes is 0 which is the number associated with \( \text{conf} \). The illustrations clearly explain the properties defined above hold.
We also illustrate the numbering of the XML document tree presented in Figure 5 according to the MDC style using the DTD specified by us in Section ??1. The resultant tree numbered according to the MDC is as shown in Figure 8. The numbering is done according to the Eq. (1) and (2). The first occurrence of the node named article gets the number 0, as $O_n = k$ (it is the first child) which is 0 and $C_n = C_{\text{parent}(n)} - O_n$ where $C_{\text{parent}(n)} = 0$, thus $C_{\text{article}} = 0$. Similarly the second occurrence of the node named thesis gets the number 0.3, as $C_{\text{parent}(n)} = 0$ with $O_{\text{presib}(n)} = 1, m = 2$ and $1 \% 2 \neq 0$, thus $O_n = O_{\text{presib}(n)} + m + k - O_{\text{presib}(n)} \% m$, i.e., $O_n = 1 + 2 + 1 - (1 \% 2) = 3$. This explains the number 0.3, similarly other node numbers can be generated.

3.2 Overview of our Algorithm

Figure 9 portrays the overview of our algorithm. After index construction, we perform three different classes of queries, incorporating slightly varying techniques.

3.3 Index Construction

The index construction proceeds by taking as input the MDC numbered XML document tree as shown in Figure 7a and Figure 8. The motive here is to preprocess the tree structure in a manner that makes execution of regular expression queries effi-
Algorithm 1  Index Construction

**Input:** XML document tree and the corresponding DTD

**Output:** CDTree: An efficient index structure for XPath queries

1: Perform DFS and calculate MDC of each entry in the XML document tree using equations 1 and 2
2: //Merge all the nodes that have the same label into a single node
3: Perform BFS
4: for nodes ∈ each level do
5: Extract the common prefix, and merge the nodes that have $O_n\%m = O_o\%m$ where $O_n, O_o$ are the remaining parts after extracting the common prefix.
6: Store the MDC values in the newly generated merged nodes
7: end for //Update all outer node labels with labeling similar to MDC, but now on the merged-tree
8: for nodes ∈ merged-tree do
9: nodelabel ← MDC(Merged − Tree)
10: end for //Create the Inverted Index
11: for unique tag-names ∈ DTD do
12: p ← (outerlabel, nodereference)
13: Populate a list of p per tag-name
14: Create a hashmap with key as tag-name and value as the list in Step 12
15: end for

Figure 10: The CDTree index structure as output by algorithm 1.

each of the merged tree nodes. We also do maintain an inverted index structure that maps all the unique tag-names in the XML schema to a list that contains node-specific information. Each entry in the list is a pair comprising of an outer label and a reference to a merged tree node. From an implementation point of view, we realize this by maintaining a hash table of tag-names mapping to a list of pairs of outer labels and node addresses. A pictorial representation of this structure is shown in Figure 11.

This facilitates efficient tree traversal while querying the index structure. A more formal description of the algorithm is mentioned in Algorithm 1. Once we have this CTree-like structure created as shown in Figure 10 we can now proceed to execute the queries. The CDTree created by us is an extension of the CTree and TJFast, with the capability of solving path, branch and wildcard queries, and thus our contribution should be considered an important one.

3.4 Query Execution

The search procedure requires the index structure created by the previous step to execute XPath queries efficiently. The search procedure is rather very simple. The querying procedure differs slightly for each category of queries – single path, branch and wildcard queries. However, the common step among each of them is the query encoding step. During index construction, a level aware transition table is also created that is capable of taking tag-names per level as input and outputting a number to encode the query. This number is exactly the same as the last component of the outer-label corresponding to the input tag-name. The motive behind this choice of the number is that,
Figure 11: The Inverted Index to facilitate efficient look-up for nodes based on the tag-name.

it aids in matching the query directly according to the outer-label components. All the queries are encoded in this fashion, with a minor exception for the wild-card queries, where the wild-card nodes are ignored and are kept as is. We now explain the query execution for each category mentioned above.

### 3.4.1 Path Query

When presented with a path query, say, `/dblp/article/title`, our query execution step first encodes the query to 0.0.0 as is clear from the outer-label of the `title` node that has the same path as the query from Figure 10. We then use the inverted index structure as represented in Figure 11 to look-up the tag-name for the leaf node of the query and retrieve the list of outer-labels and node-references corresponding to that tag. The retrieved list is then traversed and the contents of the node whose outer-label matches with the encoded query is returned. This list is sorted on the outer labels and thus the search can stop as soon as we find the answer. A pictorial representation of the path query execution is shown in Figure 12.

### 3.4.2 Branch Query

A branch query, such as `/dblp/article/[titleandyear]` consists of the `and` predicate and, thus, can be thought of as a composition of multiple single path queries. We first decompose this query into single path-queries and follow the same procedure for each of them as mentioned in Section 3.4.1. Once we have the answers from these individual queries, we then employ the merge and skip procedure to efficiently perform a join of the answers. The merge and skip procedure is depicted in Figure 13. This is easily possible since the answers (labels) returned from the single path queries are in sorted order. A pictorial representation of the branch query execution is shown in Figure 14.

### 3.4.3 Wild-card Query

Given a wild-card query, say `/dblp/*/author`, we encode it as 0.*.1. Using the inverted index, we get to the list of outer-labels for the nodes named `author` (which is the node just below the last wild-card node) and `dblp` (which is the node just above the first wild-card node). We now perform efficient matching of the outer-labels of these nodes. Since the labels are sorted, we can efficiently perform join like operations. We do not match the entire labels; rather, just the relevant components of the labels are matched. For example, for the query mentioned above only the last
component of the labels of the the dblp node are matched with the \((k-2)\)th component of the labels of the author node. The idea behind \((k-2)\)th component is that 1 is for the node itself and the other 1 is for the wildcard node and, thus, we ignore the last two components. A pictorial representation for this query execution is shown in Figure 15.

4 Experiments

All the experiments were run on an Intel(R) Xeon(R) 24-core machine with 2.4 GHz CPU and 194 GB RAM running Linux Debian 6.0.7. We present the experiments on the DBLP dataset.

Figure 16 shows the time taken to perform the different stages of our algorithm on the real DBLP dataset. The index construction roughly takes around 240 seconds, while the querying for the most part is within 100 ms. However, some of the branch queries behave abnormally due to the large amount of individual answer sets that need to be joined and intersection operation over a huge list is a costly operation. Table 1 displays the exact timing information of our experiments. All the times are reported by averaging over 10 runs.

5 Conclusions and Future Work

In this paper, we addressed the problem of indexing an XML database for efficiently solving XPath queries where the queries could be either single path, branch or wild-card queries. This is the era of the web, which explains the humongous size of practical
XML databases like the DBLP database that has millions of entries in it. Querying such a huge database with a naïve approach is impractical. Consequently, we propose an efficient indexing scheme that helps reducing the search time which may be exponential in the naïve case to a small fraction that succeeds only by traversing the height of the tree instead of the entire tree. The amount of reduction provided by the index structure justifies the initial offline cost that is spent on pre-processing and index construction, which may also be considered as a one-time cost. Our index structure executes the search queries efficiently and thus could be considered as a valuable contribution to the ongoing research.

Table 1: Time required by CDTree on the DBLP dataset.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Time (in ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Index Construction</td>
<td>237329.1</td>
</tr>
<tr>
<td>2 Path Query</td>
<td>5.7</td>
</tr>
<tr>
<td>3 Branch Query</td>
<td>12571.4</td>
</tr>
<tr>
<td>4 Wild-card Query</td>
<td>84.6</td>
</tr>
</tbody>
</table>

Figure 16: Time required to execute our algorithm on the DBLP dataset.

XML databases handle all possible XML path queries.

References


