# A Prime Number Approach to Matching an XML Twig Pattern including Parent-Child Edges

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Abstract: Twig pattern matching is a core operation in XML query processing because it is how all the occurrences of a twig pattern in an XML document are found. In the past decade, many algorithms have been proposed to perform twig pattern matching. They rely on labelling schemes to determine relationships between elements corresponding to query nodes in constant time. In this paper, a new algorithm *TwigStackPrime* is proposed, which is an improvement to *TwigStack* (Bruno et al., 2002). To reduce the memory consumption and computation overhead of twig pattern matching algorithms when *Parent-Child* (P-C) edges are involved, *TwigStackPrime* efficiently filters out a tremendous number of irrelevant elements by introducing a new labelling scheme, called Child Prime Label (CPL). Extensive performance studies on various real-world and artificial datasets were conducted to demonstrate the significant improvement of CPL over the previous indexing and querying techniques. The experimental results show that the new technique has a superior performance to the previous approaches.

## 1 INTRODUCTION

The extensible markup language XML has emerged as a standard format for information representation and communication over the internet. Due to the definition of relationships in XML as nested tags, data in XML documents are self-describing and flexibly organized (Li and Wang, 2008). The basic XML data model is a labelled and ordered tree. A query in the context of XML is defined as a complex selection on elements of an XML document specified by structural information of the selected elements (Wu et al., 2012). In most XML query languages, such as XPath and XQuery, a twig (small tree) pattern can be represented as a node-labelled tree whose edges specify the relationship constraints among its nodes and they are either *Parent-Child* or *Ancestor-Descendant*. Generally, the purpose of XML indexing is to improve the efficiency and the scalability of query processing by reducing the search space. Without an index, XML retrieval algorithms have to scan all the data. In XML, the types of structural index can be divided into two main groups; node and graph indexing. A well-known example of node indexing is range-based (Zhang et al., 2001). In a range-based labelling scheme, every node in an XML document is assigned an unique label to record its position within the original XML tree. The labelling scheme must enable determination of all structural relationships by computation. In order to detect the twig patterns, previous algorithms need to access only the labels corresponding to the query nodes without traversing the original XML tree by utilizing a clustering mechanism called *tag streaming* where all elements with the same tag are grouped together (Chen et al., 2005). The alternative usually summarizes all paths in an XML document starting from the root. Early work on processing twig pattern matching decomposed twigs into a set of binary structures, then performed structural joins to obtain individual binary matchings. The final solution of the twig query is computed by stitching together the binary matches.

In (Bruno et al., 2002), the authors introduced the first holistic twig join algorithm for matching an XML twig pattern, called *TwigStack*. It works in two phases. Firstly, twig patterns are decomposed into a set of root-to-leaf paths queries and the solutions to these individual paths are computed from the data tree. Then, the intermediate paths are merge joined to form the final result. The authors of (Bruno et al., 2002) proposed a novel prefix filtering technique to reduce the number of irrelevant elements in the intermediate paths. *TwigStack* is optimal for twig patterns when all the structural relationships are Ancestor-Descendant,

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and it guarantees all the intermediate path solutions contribute to the final result, but it generates useless intermediate path results when the twig pattern query contains Parent-Child axes.
In this paper, we proposed a new indexing technique to identify P-C relationships efficiently, called *Child Prime Labels*. We extended the original holistic twig pattern matching algorithm to process XML twig patterns with P-C axes efficiently and reduce memory consumption and CPU overheads. In addition, we have conducted an extensive set of experiments to compare the performance of the new algorithm to the previous approaches.
The rest of this paper is organized as follows: the novel indexing and twig algorithm are presented in Section 2 and Section 3, respectively. In Section 4 the experimental results are reported. The discussion of related work in Section 5, then the paper is concluded in the last section 6.

## 2 NODE LABELLING SCHEME

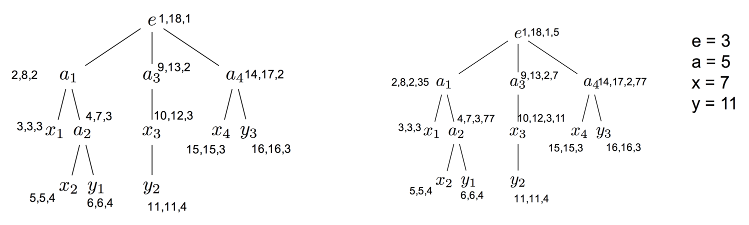
Node indexing (also referred to as a labelling or numbering scheme) is commonly used to label an XML document to accelerate XML query performance by recording information on the path of an element to capture structural relationships rapidly during query processing with no need to access the XML document physically (Lu et al., 2004). In this approach, every node in an XML document is indexed and assigned an unique label which records its positional information within an XML tree. The information gained from labels vary according to the chosen labelling scheme. Most of the previous twig join algorithms rely on labelling schemes where nodes are considered as the basic unit of a query which provides a great flexibility in performing any structural query matching efficiently.
To determine the effects of the range-based labelling scheme, (Zhang et al., 2001) proposed multi-predict merge-join algorithm based on the positional information of the XML tree. An alternative representation, a prefix scheme, of labels of an XML tree can be seen in (Lu et al., 2011). In this sort of labelling scheme, each node is associated with a sequence of integers that represents the node-ID path from the root to the node. This approach can be exemplified by Dewey, the sequence of components in a Dewey label is separated by "." where the last component is called the self label (i.e., the local order of the node) and the rest of the components are called the parent label. For instance, $\{1.2.3\}$ is the parent of $\{1.2.3.1\}$. Another approach, (Alireza Aghili et al., 2006) addressed the limitations of information encoded within labels produced by existing labelling schemes. It focus on performing join operations earlier, at leaf levels, where the selectivity of query nodes is at its peak for data-centric XML documents. The significance of the proposed approach stems from a comprehensive labelling scheme that could infer additional structural information, called *Nearest Common Ancestor, NCA for short* rather than the basic relationships among elements of XML documents. None of the previous approaches have taken the breadth of every node into account. We propose a novel approach to overcome the previous limitations. The key idea of our work is to find an appropriate, refined labelling scheme such that, for any given query node in the query, the set of its child query nodes in the XML document which forms the major bottleneck in determining structural relationship because parent-child can be resolved efficiently. This novel approach results in considerably fewer single paths stored than *TwigStack* algorithm. It also increases the overall performance and reduces the memory overhead, and the result is shown clearly in our experiments. During depth-first scanning, a node is assigned the next available prime number if its tag has not been examined. After that, we check the CPL parameter of its parent element to see whether it is divisible by the assigned prime number or not. If it is, we process the next element, otherwise the product of parent element's CPL is multiple by the new prime number. For illustration, assume we have two nodes $u$ and $v$ labelled by a triplet$(start, end, level)$ where *start* and *end* record the positional information of the opening tag and the ending tag, respectively, while *level* is the number of edge(s) to the root. A set of structural relationships can be determined as follows:

**Property 1.** ***Ancestor-Descendant and Parent-Child relationships****, For two nodes u and v encoded using the range-based labelling scheme can be described as v=( $start_u$ , $end_u$ , $level_u$ ) and u=( $start_v$ , $end_v$ , $level_v$ ). From that positional information, u is the ancestor of v if and only if $start_u < start_v < end_u$.*

**Property 2.** ***Parent-Child relationship****, From that positional information, u is the parent of v if and only if $start_u < start_v < end_u$ and $level_u + 1 = level_v$.*

**Definition 1.** ***(Child Prime Label)*** *A child prime label is assigned to each element in an XML document as an extra parameter into the range-based label. A child prime label indicates the multiplication of distinct prime numbers for every internal elements within the document. For example, node u is encoded quadruple =( $start_u$ , $end_u$ , $level_u$ , $CPL_u$ ).*

**Property 3.** *In any XML labelling scheme that is augmented with Child Prime Label, for any*



(a) (b)

Figure 1: An example of an XML tree labelled using the original range-based labelling scheme in Figure 1a and the new child prime label parameter assigned to each element along with the tag index in the top right of Figure 1b.

*nodes x,y and z in an XML document, x has at least one or more child nodes of tag(y) and tag(z) if $CPL_x$ mod $key_{tag(y)} \times key_{tag(z)} = 0$ where $key_{tag(y)}$ and $key_{tag(y)}$ are unique prime numbers.*

Figure 1a and 1b are a sample of an XML tree labelled with the original range-based and child prime label augmentation, respectively. To demonstrate the effect of child prime label, consider the XML tree in Figure 1b and the tag indexing table on the top right, queries in XML are expressed as twigs since data is represented as tree. The answer to an XML query is all occurrences of it in an XML document under investigation. So, if we issue the simple twig query $Q = a[x]/y$, only two elements will be considered for further processing, namely $a_2$ *and* $a_4$. This is because of $CPL_{a_2}$ *mod* $key_{tag(x)} \times key_{tag(y)} = 77$ *mod* $7 \times 11$ *equals* 0.

## 3 TWIG JOIN ALGORITHM

There is abstract data type called a stream, which is a set of elements with the same node label, where the elements are sorted in ascending document order. Each query node $q$ in a twig pattern is associated with an element stream, named $T_q$ which has a cursor $C_q$ which initially points to the first element in $T_q$ at the beginning of a query processing. We define the following operations on streams and query nodes to facilitate the processing. *children(q)* returns all child nodes of $q$. *subtree(q)* returns all child nodes which are in the subtree rooted at $q$. *childrenAD(q)* returns all child nodes which have ancestor-descendant relationship with $q$. *childrenPC(q)* returns all child nodes which have parent-child relationship with $q$. *isRoot(q)* tests if $q$ is the root or not. *parent(q)* returns the parent query node of $q$. *isLeaf(q)* tests if $q$ is a leaf node or not. *getStart($C_q$)* returns the start attribute of $q$. *getEnd($C_q$)* returns the end attribute of $q$. *getLevel($C_q$)* returns the level attribute of $q$. *advance($C_q$)* forward the cursor of $q$ to the next element. $eof(T_q)$ to judge whether $C_q$ points to the end of stream of $T_q$. The structure of the main algorithm, *TwigStackPrime* presented in Algorithm 2 is not much different from the original holistic twig join algorithm *TwigStack* (Bruno et al., 2002) which uses two phases to compute an answer to a twig query. *TwigStackPrime* modifies *TwigStack* in order to use *CPL*. *getNext* is an essential function which is called by the main algorithm to decide the next query node to be processed. It is fundamental to guarantee that the current label associated with the returned node is part of the final output since all the basic structural relationships are thoroughly checked by *getNext* or its supporting subroutine *getElement*. The basic *TwigStack* algorithm remains the same with the only difference being the key supporting algorithm *getNext*. The main difference between two *getNext* algorithms in *TwigStack* and *TwigStackPrime* can be summarized as follows. In *TwigStack*, element $e_n$ returned by *getNext* is considered likely to contribute to the result if and only if: it has a descendant element $e_{n_i}$ in each of the streams corresponding to its child elements where $e_{n_i}$ = *children(n)* and each of its child elements satisfies recursively the first property. While in *TwigStackPrime*, if element $e_n$ has parent-child edge(s), it has to satisfy that in *getElement* procedure (Line 30-31). Finally, all individual paths are merged to produce the final results.

### 3.1 Analysis of TwigStackPrime

In this section, we show the correctness of our algorithms. The correctness of *TwigStackPrime* algorithm can be shown analogously to *TwigStack* due to the fact that they both use the same stack mechanism. In other words, the correctness of Algorithm 2 follows from the correctness of *TwigStack* (Bruno et al., 2002). Since the *getNext()* with *CPL* increases the filtering ability of the original, we prove its correctness here, while the proof of the main algorithm is in the original work of (Bruno et al., 2002).

**Definition 2.** ***(Child and Descendant Extension)***

**Algorithm 2** getNext(q)

```
 1: if isLeaf(q) then
 2:     return q
 3: for each node $n_i$ in children(q) do
 4:     $g_i$ = getNext( $n_i$)
 5:     if $g_i \neq n_i$ then
 6:         return $g_i$
 7: $n_{max}$ = node with the maximum start value $\in$ children(q)
 8: $n_{min}$ = node with the minimum start value $\in$ children(q)
 9: while getEnd(getElement(q)) < getStart(getElement( $n_{max}$)) do
10:     advance(q)
11: if getStart(getElement(q)) < getStart(getElement( $n_{min}$)) then
12:     return q
13: else return $n_{min}$
14:
15: procedure getChildExtension(q)
16:     return the child prime label attribute of $C_q$ if exists otherwise -1
17: procedure getQNChildExtension(q)
18:     return the prime number assigned to the query node which is the prod-
    uct of its child query node prime numbers
19: procedure getElement(q)
20:     if eof( $C_q$) then return $\infty, \infty, \infty, -1$ // out of range label
21:     if childrenPC(q) > 0 then
22:         while getChildExtension(q) % getQNChildExtension(q) $\neq 0$ do
23:             advance(q)
24:     return $C_q$ – the current head element the stream of q
```

*query node q has the child and descendant extension if the following properties hold:*

- *$\forall\, n_i \in childrenAD(q)$, there is an element $e_i$ which is the head of $T_{n_i}$ and a descendant of $e_q$ which is the head of $T_q$.*
- *$\forall\ n_i \in childrenPC(q)$, there is an element $e_q$ which is the head of $T_q$ and its CPL parameter is divisible by $Key_{tag_{(n_i)}}$*
- *$\forall\, n_i \in children(q)$, $n_i$ must have the child and descendant extension.*

The above definition is a key for establishing the correctness of the following lemma:

**Lemma 1.** *For any arbitrary query node $q'$ which is returned by getNext(q), the following properties hold:*

1. *$q'$ has the child and descendant extension.*
2. *Either $q == q'$ or $q'$ violates the child and descendant extension of the head element $e_q$ of its parent($q'$).*

**Algorithm 2** TwigStackPrime

```
 1: while not end(root) do
 2:     $q_{act}$ = getNext(root)
 3:     if not isRoot(q) then
 4:         CleanStack($C_{q_{act}}$, parent($q_{act}$))
 5:     if isRoot(q) or not empty($S_{parent(q_{act})}$) then
 6:         CleanStack($C_{q_{act}}$,$q_{act}$)
 7:         moveToStack($q_{act}$)
 8:         if isLeaf($q_{act}$) then
 9:             outPathSolution
10:     else advance($q_{act}$)
11: MergeAllPaths
12: procedure cleanStack(act,q)
13:     pop any element in $S_q$ which is not the ancestor of act
14: procedure moveToStack(q)
15:     p is a pointer to the top parent stack if q is the root p is null
16:     $push(C_q, p)$ to $S_q$
17: procedure end(q)
18:     return $\forall n_i \in subtree(q) : isLeaf(n_i) \wedge eof(C_{n_i})$
```

***Proof.*** (Induction on the number of child and descendants of $q'$). If $q'$ is a leaf query node, we return it in line 2 because it verifies all the properties 1 and 2. Otherwise, we recursively have $g_i$ = *getNext($n_i$)* for each child of q in line 4. If for some i, we get $g_i \neq n_i$, and we know by inductive hypothesis that $g_i$ verifies the properties 1 and 2b with respect to q, so we return $g_i$ in line 6. Otherwise, we know by inductive hypothesis that all q's child nodes satisfy properties 1 and 2 with their corresponding sub-queries. At *getElement(q)* (line 21-23), we advance from $T_q$ all segments that do not satisfy the divisibility by the product of prime numbers in *childrenPC*$(q)$ returned from *getQNChildExtension*. After that, we advance from $T_q$ (line 9-10) all segments that are beyond the maximum start value of $n_i$. Then, if q satisfies properties 1 and 2, we return it at line 12. Otherwise, line 13 guarantees that $n_i$ with the smallest start value satisfies properties 1 and 2b with respect to start value of q's head element. □

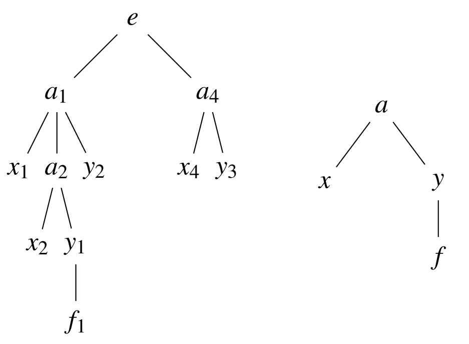
**Theorem 1.** *Given a twig pattern query Q and an XML document D, Algorithm TwigStackPrime correctly returns answer to Q on D.*

***Proof****(Sketch).* We prove Theorem 1 by using Lemma 1 and the proof of *TwigStack* to verify that the chain of stacks represents paths containing the similar chain of nodes as appear in XML document D (Bruno et al., 2002). In Algorithm *TwigStackPrime*, we repeatedly find *getNext(root)* to determine the next node to be processed. Using lemma 1, we know that all elements returned by $q_{act}$ = *getNext(root)* have the child and descendant extension. If $q_{act} \neq root$, line 4, we pop from $S_{parent(q_{act})}$ all elements that are not ancestors of $C_{q_{act}}$. After that, we already know $q_{act}$ has a child and descendant extension so that we check whether $S_{parent(q_{act})}$ is empty or not. If so, it indicates that it does not have the ancestor extension, line 5, and can be discarded safely to continue with the next iteration. Otherwise, $C_{q_{act}}$ has both the ancestor and child and descendant extensions which guarantee its participation in at least one root-to-leaf path. Then, we clean $S_{q_{act}}$ to maintain pointers from itself to the root. Finally, if $q_{act}$ is a leaf node, we compute all possible combinations of single paths with respect to $q_{act}$, line 8-9.

□

It can be shown that *TwigStackPrime* algorithm is optimal when P-C axes exist only in the deepest level of a twig query.

**Example 1.** *Consider the XML tree and a twig query in Figure 2, the head elements in their streams are $a \rightarrow a_1$, $x \rightarrow x_1$, $y \rightarrow y_1$ and $f \rightarrow f_1$. The first call*



(a) an XML tree. (b) a twig query.

Figure 2: Sub-optimal evaluation of *TwigStackPrime* where redundant paths might be generated.

*of getNext(root) inside the main algorithm will return $a \rightarrow a_1$ because it has A-D relationship with all head elements and satisfies CPL with x and y, and its descendant $y \rightarrow y_1$ also satisfies the child and descendant extension with respect to f. However, TwigStackPrime produces the useless path* $(a_1, x_1)$

## 4 EXPERIMENTAL EVALUATION

In this section we present the performance comparison of twig join algorithms, namely: *TwigStackPrime* the new algorithm based on *Child Prime Labels*, along with *TwigStack* (Bruno et al., 2002). The original twig join algorithm that was reported to have optimal worst-case processing with A-D relationship in all edges, and *TwigStackList* is the first refined version of *TwigStack* to handle P-C efficiently (Lu et al., 2004). *TwigStackList* was chosen in this experiment because it utilizes a simple buffering technique to prune irrelevant elements from the stream. We evaluated the performance of these algorithms against both real-world and artificial data sets. The performance comparison of these algorithms was based on the following metrics:

1. Number of intermediate solutions: the individual root-to-leaf paths generated by each algorithm.
2. Processing time: the main-memory running time without counting I/O costs. All twig pattern queries were executed 103 times and the first three runs were excluded for cold cache issues. We did not count the I/O cost for tag indexing files for *TwigStackPrime* algorithm because it s negligible, and the cost to read the tag indexing is constant over a series of twig pattern queries.

### 4.1 Experimental Settings

All the algorithms were implemented in Java JDK 1.8. The experiments were performed on 2.9 GHz Intel Core i5 with 8GB RAM running in Mac OS X El Capitan. The benchmarked datasets used in the experiments and their characteristics are shown in Tables 1 and 2. The selected datasets and benchmark are the most frequent in the literature of XML query processing (Bruno et al., 2002; Lu et al., 2004; Grimsmo et al., 2010; Wu et al., 2012; Li and Wang, 2008; Qin et al., 2007). We generated Random dataset similar to that in (Lu et al., 2004) but we vary the two parameters: *depth* and *fan-out*. The depth of randomly generated tree has maximum value sets to 13 and *fan-out* has range from 0 to 6, respectively. This data set was created to test the performance where the XML combines the features of DBLP and TreeBank, being structured and deeply-recursive at the same time.

Table 1: Benchmark real-world datasets used in the experiments.

| | DBLP | TreeBank |
|---|---|---|
| Rangae-based MB | 65.3 | 43 |
| CPL MB | 70.3 | 47.9 |
| $\triangle$ size MB | 5 | 4.9 |
| Tag Indexing Size KB | 0.48 | 3 |
| Nodes (Millions) | 3.73 | 2.43 |
| Max/Avg depth | 6/2.9 | 36/7.8 |
| Distinct Tags | 40 | 251 |
| Largest Prime Numbers | 151 | 1597 |

Table 2: Benchmark artificial datasets used in the experiments.

| | XMark | Random |
|---|---|---|
| Rangae-based MB | 35.3 | 69.4 |
| CPL MB | 40.1 | 74.1 |
| $\triangle$ size MB | 4.8 | 4.7 |
| Tag Indexing Size KB | 1 | 0.049 |
| Nodes (Millions) | 2.04 | 3.94 |
| Max/Avg depth | 12/5.5 | 13/7 |
| Distinct Tags | 83 | 6 |
| Largest Prime Numbers | 379 | 19 |

The XML structured queries for evaluation over these dataset were chosen specifically because it is not common for queries, which contain both '//' and '/', to have a significant difference in performance for tightly-structured document such as DBLP and XMark. TreeBank twig queries were obtained from (Lu et al., 2004) and (Grimsmo et al., 2010). Twig pattens over the random data set were also randomly generated. Table 3 shows the XPath expressions for the chosen twig patterns. The code indicates the data set and its twig query, for instance, TQ2 refers to the second query issued over TreeBank dataset.

Table 3: Benchmark twig pattern queries used in the experiments.

| Code | Query |
|---|---|
| $DQ_1$ | dblp/inproceedings[//title]//author |
| $DQ_2$ | //www[editor]/url |
| $DQ_3$ | //article[//sup]//title//sub |
| $DQ_4$ | //article[/sup]//title/sub |
| $XQ_1$ | /site/closed_auctions/closed_auction [annotation/description/text/keyword]/date |
| $XQ_2$ | /site/closed_auctions/closed_auction [//keyword]/date |
| $XQ_3$ | /site/people/person[profile[gender][age]] /name |
| $XQ_4$ | /site/people/person[profile[gender][age]] /name |
| $XQ_5$ | //item[location][//mailbox//mail//emph] /description/keyword |
| $XQ_6$ | //people/person[//address/zipcode]/profile /education |
| $TQ_1$ | //S[//MD]//ADJ |
| $TQ_2$ | //S/VP/PP[/NP/VBN]/IN |
| $TQ_3$ | //VP[/DT]//PRP_DOLLAR_ |
| $TQ_4$ | //S[/JJ]/NP |
| $TQ_5$ | //S/VP/PP[/IN]/NP/VBN |
| $TQ_6$ | //S[//VP/IN]//NP |
| $TQ_7$ | //S/VP/PP[//NP/VBN]/IN |
| $TQ_8$ | //EMPTY/S//NP[/SBAR/WHNP/PP//NN] / _COMMA_ |
| $TQ_9$ | //SINV//NP[/PP//JJR][//S]//NN |
| $RQ_1$ | //b//e//a[//f][d] |
| $RQ_2$ | //a//b[//e][c] |
| $RQ_3$ | //e//a[/b][c] |
| $RQ_4$ | //a[//b/d]//c |
| $RQ_5$ | //b[d/f]/c[e]/a |
| $RQ_6$ | //c[//b][a]/f |
| $RQ_7$ | //a[c//e]/f[d] |
| $RQ_8$ | //d[a//e/f]/c[b] |
| $RQ_9$ | //a[d][c][b][e]//f |

## 4.2 Experimental Result

We compared *TwigStackPrime* algorithm with *TwigStack* and *TwigStackList* over the above mentioned twig pattern queries against the data sets selected. The Kruskal-Wallis test is a non-parametric statistical procedure was carried out on processing time, the *p-value* turns out to be nearly zero (p-value less than 2.2 to the power of -16), it strongly suggests that there is a difference in processing time between two algorithms at least as shown in Figure 3.

### 4.2.1 DBLP and XMark Datasets

We tested twig queries over DBLP and XMark datasets, they are both considered as data-oriented and have a very strong structure. In these two datasets both *TwigStackPrime* and *TwigStackList* are optimal, but *TwigStack* still produces irrelevant paths. This can be shown in Table 4. Since there is a difference in performance, we ran pairwise comparison based on Manny-Whitney test showed that in most tested twig queries *TwigStackPrime* outperformed *TwigStackList* and *TwigStack*. *TwigStackPrime* and *TwigStackList* have same performance in $XQ_2$ , $XQ_3$ *and* $XQ_6$ see Figure 3a and 3b.

### 4.2.2 TreeBank Dataset

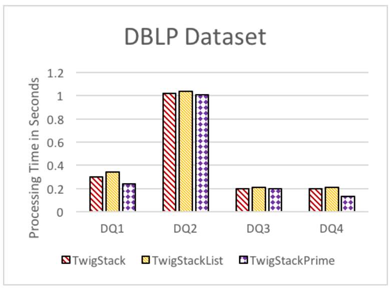
None of the algorithms compared are optimal in this dataset because TreeBank has redundant paths and many tags are deeply recursive. The number of individual paths produced by each algorithm for the twig pattern queries tested over Treebank is presented in Table 3. *TwigStackPrime* showed a superior performance in avoiding the storage of unnecessary paths while processing time is improved. $TQ_6$ is a very expensive query, it touches a very large portion of the document and the answer is quite large. Pairwise comparison based on Manny-Whitney test between *TwigStackPrime* and *TwigStackList* resulted in $p-value < .001$ which suggests a significant difference and *TwigStackPrime* has the best performance see Figure 3e. It can be seen in Figure 3d the only twig queries where *TwigStackPrime* has slower performance comparing to the others is $TQ_3$ *and* $TQ_9$ because they touch very little of the dataset.

### 4.2.3 Random Dataset

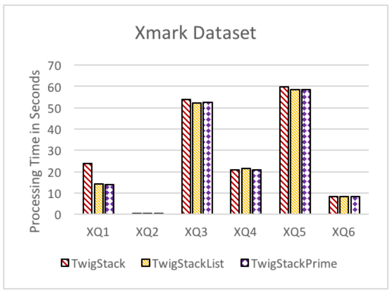
We have generated twig queries over this dataset to test the performance of the algorithms by varying the parent-child edges and increasing their numbers. *RQ4* is optimal for *TwigStackList* because it does not have P-C in branching axes, and *TwigStackPrime* does the same (see Table 3). While in *RQ9* where all branching edges are P-C, none of the algorithms compared guarantee optimal evaluation except *TwigStackPrime* in which *RQ9* is its optimal class of query. When evaluating *RQ6*, *TwigStackPrime* has the best performance, it is roughly twice as fast than *TwigStackList* and five time faster than *TwigStack* see Figure 3c and 3e.

## 5 RELATED WORK

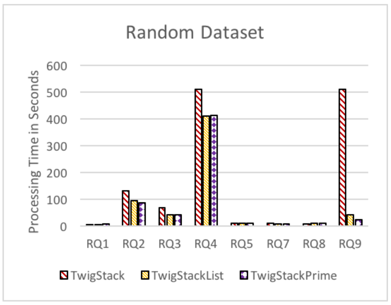
The growing number of XML documents leads to the need for appropriate XML querying algorithms. Over the past decade, most research in structured XML query processing has emphasized the use of node indexing approaches (Bruno et al., 2002; Lu et al., 2004; Grimsmo et al., 2010; Wu et al., 2012; Li and



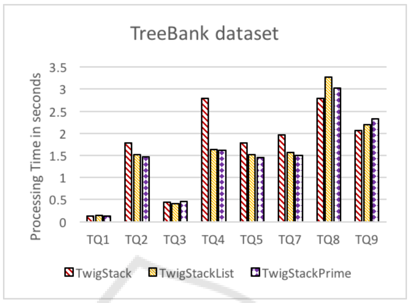
(a) DBLP.



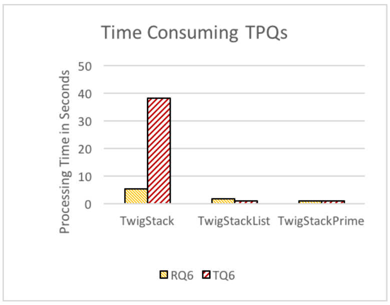
(b) XMark.



(c) Random.



(d) TreeBank.



(e) Time consuming TPQs.

Figure 3: Processing time for twig pattern queries against DBLP in 3a and XMark in 3b. 3c and 3d shows processing time for twig queries on Random and TreeBank datasets, respectively. Figure 3e illustrates the processing time taken by each algorithm to run the two most expensive queries in the experiments, normalizing query times to 1 for the fastest algorithm for each query.

Table 4: Single paths produced by each algorithm.

| Code | TwigStack | TwigStack List | TwigStack Prime |
|---|---|---|---|
| $DQ_1$ | 147 | 139 | 139 |
| $DQ_4$ | 98 | 0 | 0 |
| $XQ_1$ | 9414 | 6701 | 6701 |
| $TQ_2$ | 2236 | 388 | 441 |
| $TQ_3$ | 10663 | 11 | 5 |
| $TQ_4$ | 70988 | 30 | 10 |
| $TQ_6$ | 702391 | 22565 | 22565 |
| $TQ_8$ | 58 | 27 | 26 |
| $TQ_9$ | 29 | 17 | 8 |
| $RQ_1$ | 2076 | 1843 | 1795 |
| $RQ_2$ | 29914 | 24235 | 23057 |
| $RQ_3$ | 20558 | 16102 | 15505 |
| $RQ_4$ | 67005 | 57753 | 57753 |
| $RQ_5$ | 3765 | 901 | 1093 |
| $RQ_6$ | 201835 | 98600 | 72084 |
| $RQ_7$ | 6880 | 2791 | 3219 |
| $RQ_8$ | 746 | 322 | 406 |
| $RQ_9$ | 179546 | 26114 | 8786 |

Wang, 2008; Qin et al., 2007). One of the most important problems in XML query processing is tree pattern matching. Generally, tree pattern matching is defined as mapping function $M$ between a given tree pattern query $Q$ and an XML data $D$, $M: Q \rightarrow D$ that maps nodes of $Q$ into nodes of $D$ where structural relationships are preserved and the predicates of $Q$ are satisfied. Formally, tree pattern matching must find all matches of a given tree pattern query $Q$ on an XML document $D$. The classical holistic twig join algorithm *TwigStack* only considers the ancestor-descendant relationship between query nodes to process a twig query efficiently without storing irrelevant paths in intermediate storage. It has been reported (Bruno et al., 2002) that it has the worst-case I/O and CPU complexities when all edges in twigs are "//" (AD relationship) linear in the sum of the size of the input and output lists. However, TwigStack's performance suffers from generating useless intermediate results when twig queries encounter Parent-Child relationships. The authors of (Lu et al., 2004) proposed a new buffering technique to process twig queries with *P-C* relationships more efficiently by looking ahead some elements with *P-C* in lists to eliminate redundant path solutions. *TwigStackList* guarantees every single path generated is a part of the final result if twig queries do not have *P-C* under branching query nodes (Lu et al., 2004). The authors of (Choi et al., 2003) have proven that the *TwigStack* algorithm and its variants which depend on a single sequentially scan of the input lists can not be optimal for evaluation of tree pattern queries with any arbitrary combination of ancestor-descendant and parent-child relationships. However, the approach to examine XML queries against document elements in post-order was first introduced by (Chen et al., 2006), *Twig*$^2$*Stack*. The decomposition of twigs into a set of single paths and the enumeration of these paths is not necessary to process twig pattern queries. The key idea of their approach is based on the proposition that when visiting document elements in post-order, it can be determined whether or not they contribute to the final result before storing them in intermediate storage, which is trees of stacks, to ensure linear processing. *TwigList* (Qin et al., 2007) replaced the complex intermediate storage proposed in *Twig*$^2$*Stack* with lists (one for every query node) and pointers with simple intervals to capture structural relationships. The authors in (Grimsmo et al., 2010) proposed a new storage scheme, level vector split which splits the list connected to its parent list with *P-C* edge to a number of levels equals to the depth of the XML tree.

## 6 CONCLUSION

In this paper we have proposed a new mechanism to improve the pre-filtering strategy in twig join algorithms when *P-C* edges exist in twig patterns. The new technique has the ability to ensure pruning of unnecessary elements from the streams which can enhance runtime efficiency and relieve memory consumption by avoiding the storage of redundant paths. We are currently working to extend our approach to combine with the previous orthogonal algorithms to propose a new one-phase twig join algorithm that we hope will be faster in average worst-case than the previous algorithms. Furthermore, we plan to examine processing ordered twig patterns and positional predicate in a way that would consume less time and memory than the existing approaches.

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