APEX: An Adaptive Path Index for XML data

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ABSTRACT

The emergence of the Web has increased interests in XML data. XML query languages such as XQuery and XPath use label paths to traverse the irregularly structured data. Without a structural summary and efficient indexes, query processing can be quite inefficient due to an exhaustive traversal on XML data. To overcome the inefficiency, several path indexes have been proposed in the research community. Traditional indexes generally record all label paths from the root element in XML data. Such path indexes may result in performance degradation due to large sizes and exhaustive navigations for partial matching path queries start with the self-or-descendent axis("//").

In this paper, we propose APEX, an adaptive path index for XML data. APEX does not keep all paths starting from the root and utilizes frequently used paths to improve the query performance. APEX also has a nice property that it can be updated incrementally according to the changes of query workload. Experimental results with synthetic and real-life data sets clearly confirm that APEX improves query processing cost typically 2 to 54 times better than the traditional indexes, with the performance gap increasing with irregularity of XML data.

1. INTRODUCTION

The Extensible Markup Language (XML) is becoming the dominant standard for exchanging data over World Wide Web. Due to its flexibility, XML is rapidly emerging as the *de facto* standard for exchanging and querying documents on the Web required for the next generation web applications including electronic commerce and intelligent web searching. XML data is an instance of *semistructured data* [1]. XML documents comprise hierarchically nested collections of *elements*, where each element can be either atomic (i.e., raw character data) or composite (i.e., a sequence of nested subelements). *Tags* stored with elements in an XML document describe the semantics of the data. Thus, XML data, like semistructured data, is hierarchically structured and self-describing.

Several XML query languages [2, 4, 6, 7, 10] have been also proposed recently. XML Query languages such as XPath [7] and XQuery [4] use path expressions to traverse irregularly structured XML data. Thus, the navigation of irregularly structured graph is one of essential components for processing XML queries. Since the objects may be scattered at different locations in the disk, processing XML queries may result in significant performance degradation. Furthermore, query processing with a label path for partial matching is very inefficient due to the navigation of an entire XML data graph. However, structural summaries or path indexes can speed up query evaluation on XML data by restricting the search to only relevant portion of the XML data. Thus, the extraction of the structural summary and index structures for the semistructured data in order to improve the performance of query processing have received a lot of attention recently. Examples of such index structures include DataGuides [13], T-indexes [18], the Index Fabric [8], and extensions of inverted indexes [16, 22]. The details on these index structures are described in Section 2.

DataGuides and 1-indexes are in the category of generalized path indexes that represent all paths starting from the root in XML data. They are generally useful for processing queries with path expressions starting from the root. However, these indexes are very inefficient for processing queries with partial matching due to the exhaustive navigation of the indexes. Furthermore, these path indexes are constructed with the use of data only. Therefore, they do not take advantages of query workload to process frequent path expressions effectively.

Our Contributions. In this paper, we propose APEX which is an Adaptive Path indEx for XML data. APEX does not keep all paths starting from the root and utilizes frequently used paths to improve the query performance. In contrast to the traditional indexes such as DataGuides, 1-indexes and the Index Fabric, it is constructed by utilizing the data mining algorithm to summarize paths that appear frequently in query workload. APEX also guarantees to maintain all paths of length two so that any label path query can be evaluated by joins of extents in APEX without scanning original data. APEX has the following novel

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combination of characteristics that effectively capture query workload to improve the performance of processing queries.

- **Efficient Processing of Partial Matching Queries:** Since traditional path indexes keep all label paths from the root element, they are efficient to handle queries with a simple path expression which is a sequence of labels starting from the root of the XML data. However, partial matching queries with the self-or-descendent axis("//") should be rewritten to queries with simple path expressions. In contrast to traditional path indexes, APEX is designed to support these path expressions efficiently.
- **Workload-Aware Path Indexes:** Traditional path indexes for semistructured data are constructed with the use of data only. Therefore, it is very difficult to tune the indexes toward efficient processing of frequently used queries. In APEX, frequent path expressions in query workload are taken into account using the sequential pattern mining technique [3, 12] so that the cost of query processing can be improved significantly.
- **Incremental Update:** When we decide to rebuild APEX due to query workload changes, we do not build APEX from the scratch. Instead, APEX is incrementally updated in order to minimize the overhead of construction.

We implemented our APEX and conducted an extensive experimental study with both real-life and synthetic data sets. Experimental results show that APEX improves query processing cost typically 2 to 54 times better than the traditional indexes, with the performance gap increasing with irregularity of XML data.

The remainder of the paper is organized as follows. In Section 2, we discuss related work. In Section 3, we present the data model and basic notations for APEX. We present an overview of APEX in Section 4 and describe the construction algorithms for APEX in Section 5. Section 6 contains the results of our experiments, showing the effectiveness and comparing the performance of APEX to traditional path indexes. Finally, Section 7 summarizes our work.

2. RELATED WORK

Many database researchers developed various path indexes to support label path expressions. Goldman and Widom [13] provided a path index, called the strong DataGuide. The strong DataGuide is restricted to a simple label path and is not useful in complex path queries with several regular expressions [18]. The building algorithm of the strong DataGuide emulates the conversion algorithm from the nondeterministic finite automaton (NFA) to the deterministic finite automaton (DFA) [14]. This conversion takes linear time for tree structured data and exponential time in the worst case for graph structured data. Furthermore, on very irregularly strucutured data, the strong DataGuide may be much larger than the original data.

Milo and Suciu [18] provided another index family (1/2/T-index). Their approach is based on the *backward simulation* and the *backward bisimulation* which are originated from the graph verification area. The 1-Index coincides with the strong DataGuide on tree structured data. The 1-Index can be considered as a non-deterministic version of the strong DataGuide.

In object-oriented databases, access support relations [15] are used to support frequently used reference chains between two object instances. Therefore, it materializes access paths of arbitrary lengths and thus it can be used for indexing XML documents. Note that access support relations and the T-index support only predefined subsets of paths.

Cooper et al. [8] presented the Index Fabric which is conceptually similar to the strong DataGuide in that it keeps all label paths starting from the root element. The Index Fabric encodes each label path to each XML element with a data value as a string and inserts the encoded label path and data value into an efficient index for strings such as the Patricia trie. The index block and XML data are both stored in relational database systems. Evaluation of queries encodes the desired path traversal as a search key string and performs a lookup. The Index Fabric loses the parent-child relationships among elements since it does not keep the information of XML elements which do not have data values. Thus, the Index Fabric is not efficient for processing partial matching queries.

The many queries on XML data has the partial matching path expression because users of XML data may not be concerned with the structure of data and intentionally make the partial matching path expression to get intended results. Since the strong DataGuide, the 1-Index, and the Index Fabric record only paths starting from the root in the data graph, the query processor rewrites partial matching path queries into the queries with simple path expressions by the exhaustive navigation of index structures [11, 17]. This results in performance degradation. In contrast, APEX is constructed from label paths which are frequently used in query workload. Thus, APEX is very effective for queries with partial matching expressions.

3. PRELIMINARY

In this section, we describe our representation of XML data and define some basic notations to explain our proposed index.

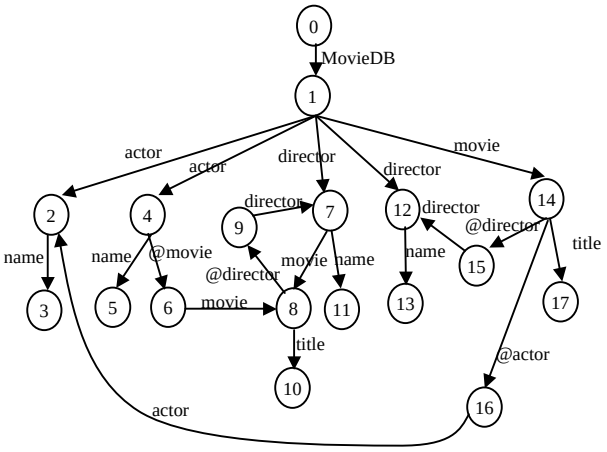
As shown in Figure 1, we represent the structure of XML data as the labeled directed graph which is similar to the OEM model [21]. Particularly, two particular attributes, ID and IDREF, allow us to represent the structure of XML data as a graph.

Definition 1. The structure of XML data is represented by the directed labeled edge graph G_{XML}. $G_{XML} = (V, E, root, A)$, $V = V_c \cup V_a$ where V_c is the universe of non-leaf nodes and V_a is the universe of leaf nodes, $E \subseteq V_c \times A \times V$ where A is the universe of labels, $root \in V$ is the root of G_{XML}. Each node in G_{XML} has a unique node identifier (nid). ■

Since XML elements are ordered and the results of XML queries must be in document order, each node keeps the document-order information. And nodes returned by the index are sorted using this information as a post-processing step. As shown in Figure 1, the reference relationship (i.e., ID-IDREF) is represented as a edge from a node for an IDREF typed attribute to a node for an element which has the corresponding ID typed attribute. In addition, the label of the edge from an element to IDREF typed child node

```
<MovieDB>
    <actor id = "a1">
        <name> actor1 </name></actor>
    <actor id = "a2" ,movie = "m1">
        <name> actor2 </name></actor>
    <director id = "d1">
        <name> director1</name>
        <movie id = "m1" director = "d1">
            <title> movie2 </title></movie></director>
    <director id = "d2">
        <name> director2</name></director>
    <movie id = "m2" actor = "a1" , director = "d2">
        <title> movie1</title></movie>
</MovieDB>
```

(a) XML data



(b) Representation of XML data structure

Figure 1: A sample XML data

starts with '@' and the edge for the reference relationship has the normal tag, which is the tag for the target node, as it label.

Definition 2. A *label path* of a node o in G_{XML}, is a sequence of one or more dot-separated labels $l_1.l_2 \dots l_n$, such that we can traverse a path of n edges $(e_1 \dots e_n)$ from o, where the edge e_i has the label l_i. ■

In Figure 1, *movie.title* and *name* are both valid label paths of node 7. In XML data, queries are based on label paths such as *//movie/title*.

Definition 3. A *data path* of a node o in G_{XML} is a dot-separated alternating sequence of labels and nids of the form $l_1.o_1.l_2.o_2 \dots l_n.o_n$, such that we can traverse from o a path of n edges $(e_1 \dots e_n)$ through n nodes $(x_1 \dots x_n)$, where the edge e_i has the label l_i and the node x_i has the nid o_i. ■

In Figure 1, *movie.8.title.10* and *name.11* are data paths of node 7.

Definition 4. A data path d is an *instance* of a label path l if the sequence labels made from d by eliminating nids is equal to l. ■

Again in Figure 1, *movie.8.title.10* is an instance of *movie.title* and *name.11* is an instance of *name*.

Definition 5. A label path $A = a_1.a_2 \dots a_n$ is *contained* in another label path $B = b_1.b_2 \dots b_m$ if we have $a_1 = b_i, a_2 = b_{i+1}, \dots, a_n = b_{i+n-1}$ where $1 \leq i$ and $i+n-1 \leq m$. When A is contained in B, we also call that B *contains* A or A is a *subpath* of B. Furthermore, when A is a subpath of B and $m = i + n - 1$, we call that A is a *suffix* of B. ■

For example, the label path *movie* is a subpath of *movie.title*. And, the label path *title* is a suffix of *movie.title*.

4. OVERVIEW OF APEX

In this section, we propose an example and the formal definition of APEX.

An example of APEX for Figure 1 is shown in Figure 2 when the required paths $= A \cup \{$*director.movie, @movie.movie, actor.name*$\}$ (see Definition 6). It is not necessary to know how to construct APEX at this point. The purpose of this example is to help understanding the definitions in this section.

As shown in Figure 2, APEX consists of two structures : a graph structure (G_{APEX}) and a hash tree (H_{APEX}). G_{APEX} represents the structural summary of XML data. It is useful for query pruning and rewriting. H_{APEX} represents incoming label paths to nodes of G_{APEX}. H_{APEX} consists of nodes, called the *hnode* and each hnode contains a hash table. In an hnode, each entry of the hash table points to another hnode or a node of G_{APEX} but not both. That is, each node of G_{APEX} maps to an entry of an hnode of H_{APEX}. H_{APEX} is a useful structure to find a node of G_{APEX} for given label path. Furthermore, H_{APEX} is useful at the incremental update phase (see details in Section 5.2). Also, each node of G_{APEX} corresponds to an extent. The extent is similar to the materialized view in the sense that it keeps the set of edges whose ending nodes are the result of a label path expression of the query.

The strong DataGuide and the 1-Index of Figure 1 are shown in Figure 3. Note that, the strong DataGuide is larger than the original data and the 1-Index is equal to the structure graph of XML data. The following XPath query q1 is an example query that retrieves all actors' names.

q1: //actor/name

To compute q1 on the strong DataGuide in Figure 3(a), the edge lookup occurs 14 times on the index structure to prune and rewrite q1 at compile-time [17]. The query processor obtains the extent for *MovieDB.actor.name*. The behavior of query processor on the 1-Index is similar to that of the strong DataGuide.

However, APEX in Figure 2 is very efficient to compute q1 since the query processor just looks up the hash tree with *actor.name* in the reverse order. That is, the hash tree of APEX enables efficient finding of the nodes of G_{APEX} for partial matching path queries.

Since making an effective index structure for all the queries is very hard, APEX changes its structure according to the frequently used paths. To extract frequently used paths, we assume that a database system keeps the set (= workload) of queries (=label paths). Furthermore, we adopt the *support* concept of the sequential pattern mining to identify frequently used paths [3, 12].

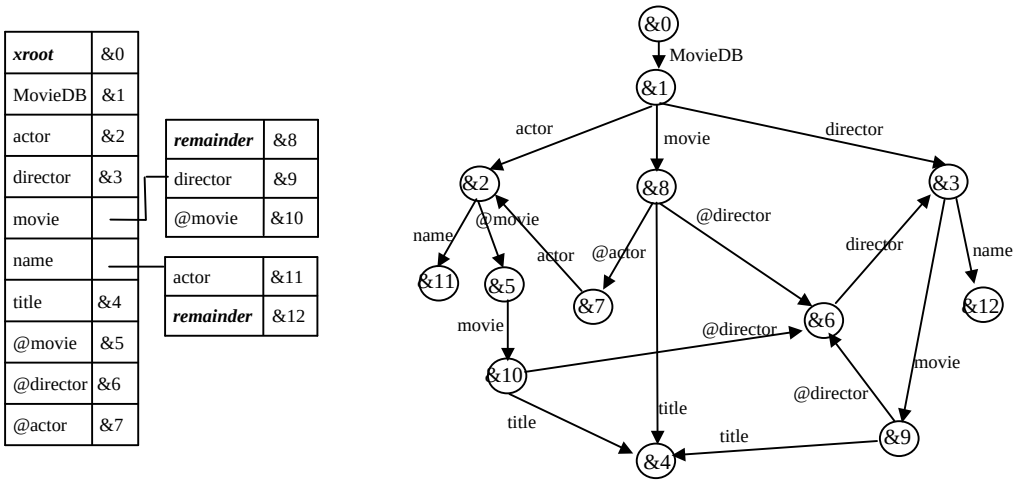
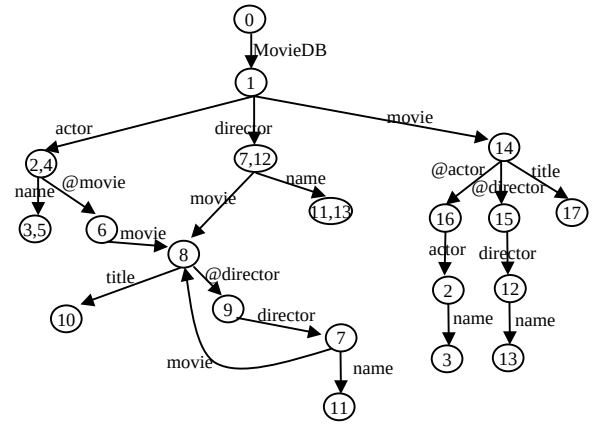
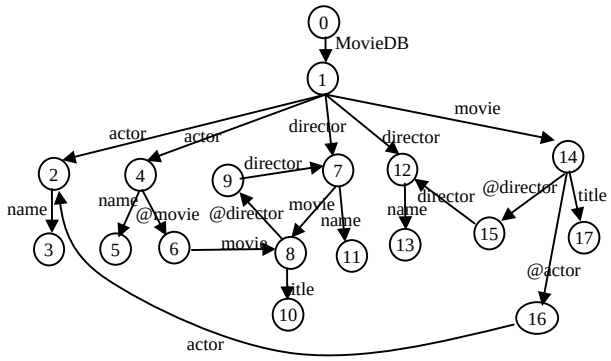


Figure 2: An example of APEX



(a) Strong DataGuide



(b) 1-Index

Figure 3: Path indexes for the sample XML data

Let the support of a label path p = $l_i \ldots l_j$, denoted by $sup(p)$, be the ratio of the number of queries having p as a subpath to the total number queries. Also, let `minSup` denote the user-specified minimum support.

Definition 6. A label path $p = l_i \ldots l_j$ in G_{XML} is a *frequently used path* if $sup(p) \geq$ `minSup`. Let p be a *required path* if it is either a frequently used path or the length of p is one. ■

Definition 7. For a label path p of the form $l_i.l_{i+1} \ldots l_j$ in G_{XML}, a edge set, $T(p)$, is $\{ < o_{j-1}, o_j > | \, l_i.o_i \ldots l_{j-1}.o_{j-1}.l_j.o_j$ is a data path in G_{XML} $\}$. That is, a edge set $T(p)$ is a set of pairs of nids for the incoming edges to the last nodes that are reachable by traversing a given label path p. ■

For example, the edge set $T(title)$ in Figure 1 is {<8,10>, <14,17>}. Label paths from *root* to 10 and 17 are *MovieDB .movie.title*, *MovieDB.director.movie.title*, *MovieDB.actor. @movie.movie.title*, *MovieDB.director.movie.@director.director. movie.title,* ... . And, the common suffix of these label paths is "title".

Definition 8. Given a required path set R, a label path $p \in R$ is a *maximal suffix in* R if there is no path $q \in R$ of which p is a suffix except p. ■

For example, in Figure 2, we assume that the required paths = $A \cup \{$*director.movie, @movie.movie, actor.name*$\}$. In this case, *actor.name* is a maximal suffix in the required paths since a required path whose suffix is *actor.name* does not exist except *actor.name*.

Definition 9. Let Q_{XML} be a set of label paths of the root node in G_{XML}. For each label path p in the required path set R, let $Q_G(p) = \{ \, l \mid l \in Q_{XML}$ s.t. p is a suffix of $l \}$, let $Q_A(p) = \{ \, l \mid l \in Q_{XML}$ s.t. every path q ($\neq p$) $\in R$ having p as a suffix is a suffix of l $\}$, and let $Q(p) = Q_G(p) - Q_A(p)$. Finally, a *target edge set*, $T^R(p) = \cup_{r \in Q(p)} T(r)$. ■

Consider a subset of required paths Q = $\{ \, q \mid q = l_i \ldots l_j$ whose common suffix is $p = l_k \ldots l_j \}$. That is, p is not

a maximal suffix in the required paths. Since $T(q) \subseteq T(p)$, making each edge set $T(q)$ and $T(p)$ increases the storage overhead. Thus, we make $T^R(p)$ instead of $T(p)$. Note that, if p is a maximal suffix in the required paths, $T(p) = T^R(p)$ since $Q_A(p) = \{\}$. If p is not a maximal suffix in the required paths, $T^R(p)$ is pointed to by a *remainder* entry of H_{APEX}.

Again in Figure 2, we assume that *name* and *actor.name* are required paths. Thus, as shown in Figure 1, $T(actor.name)$ = {<2,3>, <4,5>}, and $T(name)$ = {<2,3>, <4,5>, <7,11>, <12,13>}. In this case, $T^R(actor.name) = T(actor.name)$ since $Q_A(actor.name) = \{\}$.

However, $T(name) \neq T^R(name)$. By definition 9, $Q_G(name)$ = { *MovieDB.director.name*, *MovieDB.actor.name*, *MovieDB. movie.@actor.actor.name*, ... }, and $Q_A(name)$ = { *MovieDB. actor.name*, *MovieDB. movie.@actor.actor.name* } since *actor.name* is a required path and has *name* as a suffix. Then $Q(name)$ = { *MovieDB.director.name*, *MovieDB.director.movie. @director.director.name*, ... }. Thus, $T^R(name)$ = {<7,11>, <12,13>}.

Now, we will define APEX.

Definition 10. Given a G_{XML} and a required path set R, APEX can be defined as follows. We introduce the root node of G_{APEX}, *xroot* in APEX which corresponds to the root node of G_{XML}. By considering every required path $p \in$ R, we introduce a node of G_{APEX}, with an incoming label path p, that keeps $T^R(p)$ as an extent only if $T^R(p)$ is not empty. For each edge $v.l.v'$ in G_{XML}, there is an edge $x.l.x'$ in APEX where the target edge set of x' contains $< v, v' >$ and the target edge set of x contains $< u, v >$ where u is a parent node of v. ■

The following theorem proves that APEX is sufficient for the path index. By the definition of the simulation [5], if there is a simulation from G_{XML} to G_{APEX}, all the label paths on G_{XML} exist on G_{APEX}. Thus, all queries based on label paths can be evaluated on APEX.

THEOREM 1. *There is a simulation from G_{XML} to G_{APEX}.*

PROOF. Given $G_{APEX} = (V_x, E_x, xroot, A)$ and $G_{XML} = (V, E, r, A)$, there is a simulation from r to *xroot*. Suppose, there is a simulation from $v \in V$ to $x \in V_x$, a full label path q to v is $l_1 \ldots l_m$, and $\exists\ v.l_{m+1}.v' \in E$. By Definition 10, there is a node x' for T(p' = l_i ... l_{m+1} where $1 \leq i \leq$ m) whose incoming path is p', and $\exists\ x.l_{m+1}.x' \in E_x$. Therefore, there is a simulation from G_{XML} to G_{APEX}. □

Furthermore, G_{APEX} satisfies the following theorem.

THEOREM 2. *All the label paths whose lengths are 2 on G_{APEX} are on G_{XML}.*

PROOF. Recall that APEX groups the edges with respect to the incoming label paths. By Definition 10, $\forall$ edge $x.l_j.x'$ $\in E_x$, $\exists\ v.l_j.v' \in E$. By Definition 6, an incoming label path of x is a label of incoming edge of x. Therefore, by letting the label of incoming edge of u be l_i, the label path $l_i.l_j$ exists on G_{XML}. □

APEX is a general path index since APEX minimally keeps all the label paths whose length is 2 and maximally keeps all the label paths on G_{XML} corresponding to the frequently used paths. Thus, any label path query can be evaluated by look-up of H_{APEX} and/or joins of extents.

5. CONSTRUCTION AND MANAGEMENT OF APEX

The architecture of the APEX management tool is illustrated in Figure 4. As shown in the figure, the system consists of three main components: the initialization module, the frequently used path extraction module and the update module.

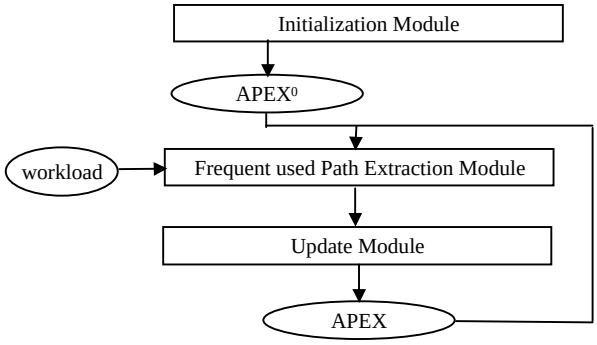


Figure 4: Architecture of APEX Management tool

The initialization module is invoked without query workload only when APEX is built first. This module generates APEX^0 that is the simplest form of APEX and is used as a seed to build a more sophisticated APEX. As query workload is collected with the use of the current APEX, the frequently used paths are computed and used to update the current APEX dynamically into a more detailed version of APEX. The last two steps are repeated whenever query workload changes.

5.1 APEX^0: Initial Index Structure

APEX^0 is the initial structure to build APEX. This step is executed only once at the beginning. Since there is no workload at the beginning, the required path set has paths of size one that is equivalent to the set of all labels in the XML data.

label	xnode
xroot	&0
MovieDB	&1
actor	&2
director	&3
movie	&8
name	&9
title	&4
@movie	&5
@director	&6
@actor	&7

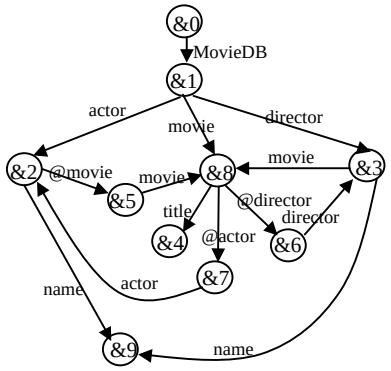


Figure 5: An example of APEX^0

An example of the APEX^0 for the XML data in Figure 1 is presented in Figure 5. The structure of APEX^0 is similar to the 1-*Representative Object* (1-RO) proposed as a structural summary in [19]. As 1-RO contains all paths of size two in the XML data, APEX^0 includes every required path of size two. However, in APEX, we have not only the

structural summary in G_{APEX} but also the extents in the nodes of G_{APEX}.

The algorithm of building APEX^0 is shown in Figure 6. Each node in APEX^0 represents a set of edges that have the same incoming label. Basically, we traverse every node in XML data (G_{XML}) in the *depth first* fashion. We first visit the root node of XML data (G_{XML}) and generate the root node for G_{APEX} first. We add an edge <NULL,*root* > to the extent of the root node in G_{APEX}. Since each node in G_{APEX} represents a unique label and there is no incoming label for the root node of APEX, we represent the root node with a special incoming label 'xroot' for convenience. We then call the function *exploreAPEX*0 with the root node in G_{APEX} and the extent of the root node in G_{APEX}.

```
Procedure buildAPEX0(root)
begin
1.  xnode := hash('xroot')
2.  xnode.extent := {< NULL, root >}
3.  exploreAPEX0(xnode, xnode.extent)
end

Procedure exploreAPEX0(x, ΔESet)
begin
1.  EdgeSet := ∅
2.  for each < u, v >∈ ΔESet do
3.      ESet := ESet ∪ {o | o is an outgoing edge from v}
4.  for each unique label l in ESet do {
5.      y := hash(l)
6.      if (y = NULL) {
7.          y := newXNode()
8.          insert y into hash table
9.      }
10.     make_edge(x, y, l)
11.     ΔnewESet := a set of edges having l in EdgeSet - y.extent
12.     y.extent := y.extent ∪ ΔnewESet
13.     exploreAPEX0(y, ΔnewESet)
14. }
end
```

Figure 6: An algorithm to build APEX^0

In each invocation of *exploreAPEX0*, we have two input arguments: the newly visited node x in G_{APEX} and new edges just added to the extent of x in the previous step. We traverse all outgoing edges from the end point of the edges in $\Delta ESet$ and group them by labels. Then we process edges in each group having the same label l one by one. Let us assume that the node representing the label l in G_{APEX} is y.

Intuitively, we need to put the edges having the label l to the extent of y and connect x and y in G_{APEX}. Then, we call *exploreAPEX0* recursively with y and the newly added edges to the extent of y. We give only newly added edges at this step as $\Delta ESet$ for recursive invocation of *exploreAPEX0* since the outgoing edges from the edges included previously to the extent have been all traversed already.

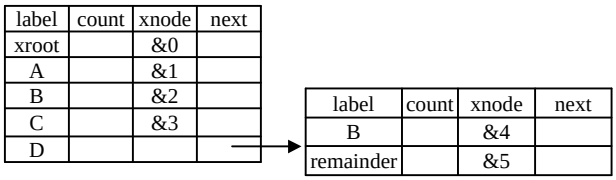
When we consider the edges for each partition with a distinct label, we have to check whether the node y exists already. To find this, we can maintain a hash table and use it. In case, the node y for the label l does not exist, we generate a new node and put it to G_{APEX}. We also make sure that the new node can be located quickly by inserting the node into H_{APEX}. The *hash* at Line (5) in Figure 6 is the hash function which returns a node for a given label. The procedure *make_edge* makes an edge from x to y with label l. For preventing the infinite traversal of cyclic data, we do not consider the edges which are already in the extent of the node y.

5.2 Frequently Used Path Extraction

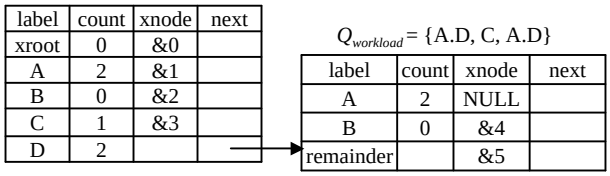
Any sequential pattern mining algorithms such as the one in [3, 12] may be used to extract frequently used paths from the path expressions appearing in query workload. While we need to use the traditional algorithms with the *anti-monotonicity* property [20] for pruning, we have to modify them.

Consider a mail order company. Assume that many customers buy A first, then B and finally C. In the traditional sequential pattern problem, when a sequence of (A, B, C) is frequent, all subsequences of size 2 (i.e.,(A, B), (A, C) (B, C)) including (A, C) are frequent. However, for the problem of finding frequently used path expressions, it is not valid any more. In other words, even though the path expression of $A.B.C$ is frequently used, the path expression of $A.C$ may not be frequent. Therefore, in case that we want to use traditional data mining algorithms which use the anti-monotonicity pruning technique, we need a minor modification to handle the subtle difference.

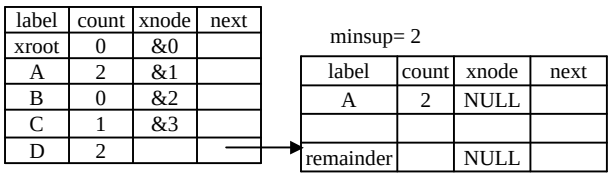
Actually, we also found that the size of query workload is not so large as that of data for sequential pattern mining applications. Thus, we used a naive algorithm in our implementation that simply counts all sequential subsequences that appear in query workload by one scan.



(a) Current state



(b) After frequency count



(c) After pruning

Figure 7: The behavior of frequently used path extraction

The basic behavior of the frequently used path extraction module is described in Figure 7. Suppose that the required path set was {A, B, C, D, $B.D$}. Then, the current state of H_{APEX} is represented as Figure 7-(a). A label path $B.D$ is represented as an entry in the subnode of D entry in the root node($HashHead$) of H_{APEX}.

Each entry of hash table in a node of H_{APEX} consists of five fields: *label, count, new, xnode*, and *next*. The *label* field keeps the key value for the entry. The *count* field keeps the frequency of label path which is represented by the entry. The *new* field is used to check a newly create entry in a node of H_{APEX}. The *xnode* field points to a node in G_{APEX} whose incoming label path is represented by the entry. Finally, The *next* field points another node in H_{APEX}. For simplicity, we omit *new* fields in Figure 7.

Let the workload $Q_{workload}$ become {$A.D$, C, $A.D$}. We first count the frequency of each label path which appeared in $Q_{workload}$ and store the counts in H_{APEX}. When we count, we do not use the *remainder* entry for counting. Figure 7-(b) shows the status of H_{APEX} after the frequency count.

Finally, we prune out the label paths whose frequency is less than `minSup`. The status of H_{APEX} after pruning is illustrated in Figure 7-(c). Assume that `minSup` is 0.6, the label path whose frequency is less than 2 is removed. Thus, a label path $B.D$ is pruned. However, label paths B and C still remain since a label path of size 1 is always in the required path set. Also, in the pruning step, the *xnode* fields, which are not valid any more by the change of frequently used paths, are set to NULL. The content for T^R(D) in Figure 7-(a) representing *remainder.D* in H_{APEX} is the set of edges whose end nodes are reachable by traversing a label path D but not $B.D$. However, the content for T^R(D) in Figure 7-(c) should be changed to the set of edges whose end nodes are reachable by traversing a label path D but not $A.D$. Thus, we set this *remainder* entry to NULL to update it later.

The algorithm of frequently used path extraction is presented in Figure 8. To extract frequently used paths in the given workload ($Q_{workload}$), the algorithm first sets *count* fields to 0 and *new* fields to FALSE of all entries in H_{APEX}.

The algorithm consists of two parts; the first part counts frequencies and the second part is the pruning phase. H_{APEX} is used to keep the change of the workload. The algorithm invokes the procedure *frequencyCount* to count the frequency of each label path and it's subpaths in $Q_{workload}$. In this procedure, the *new* field of a newly created entry in a node in H_{APEX} sets to TRUE to identify a newly created entry in a node in H_{APEX} during pruning phase.

The function *pruning*H_{APEX} removes the hash entry whose frequency is less than the given threshold `minSup`(Line (4)-(5)). Even though the frequency of an entry in the root node ($HashHead$) of H_{APEX} is less than `minSup`, it should not be removed since a label path of size 1 should be always in the required path set by Definition 6. If the frequency of an entry of the node in H_{APEX} is less than `minSup` and the entry is not in the root node, the entry is removed from the hash node by the function *hnode.delete* (Line (6)-(7)). If all entries in a node of H_{APEX} except *remainder* entry are removed by the function *hnode.delete*, *hnode.delete* returns TRUE. And then we remove this node of H_{APEX} (Line (10)-(11)).

Finally, it sets the *xnode* field to NULL because it points

```
Procedure frequentlyUsedPathExtraction()
begin
1.  reset all count fields to 0 and new fields to FALSE
2.  frequencyCount()
3.  pruning H_APEX(HashHead)
end

Function pruning H_APEX(hnode)
begin
1.  is_empty := FALSE
2.  if hnode = NULL return is_empty
3.  for each entry t ∈ hnode do
4.     if (t.count < minsup) {
5.        t.next := NULL
6.        if (t ∉ HashHead) {
7.           is_empty := hnode.delete(t)
8.        }
9.     } else {
10.       if (pruning H_APEX(t.next) = TRUE)
11.          t.next := NULL
12.       if (t.next ≠ NULL) and (t.xnode ≠ NULL)
13.          t.xnode := NULL
14.       if (t.new = true) and (hnode.remainder.xnode ≠ NULL)
15.          hnode.remainder = NULL
16.    }
17. }
18. return is_empty
end
```

Figure 8: Frequently Used Path Extraction Algorithm

to the wrong node in G_{APEX}. As mentioned early, contents of some nodes of G_{APEX} may be affected by the change of frequently used paths. There are two cases. A label path q was maximal suffix previously but it is not anymore. This is captured by that an entry has not NULL value in both *xnode* and *next* fields (Line (12)-(13)). In this case, the algorithm sets the *xnode* field to NULL to update the *xnode* field appropriately later. The second case is when a new frequently used path influences the contents of the node of G_{APEX} for the *remainder* entry in the same node of H_{APEX} since the contents of *remainder* is affected by the change of frequently used path. This is represented by that a new entry is appeared in the node of H_{APEX} and *remainder* entry in this node points to a node in G_{APEX} using the *xnode* field (Line (14)-(15)). In this case, the algorithm sets the content of the *xnode* field in *remainder* entry to NULL to update it later.

5.3 The Update with Frequently Used Paths

After the entries in H_{APEX} was updated with frequently used paths computed from the changes of query workload, we have to update the graph G_{APEX} and *xnode* fields of entries in the nodes of H_{APEX} that locates the corresponding node in G_{APEX}.

Each entry in a node of H_{APEX} may have a pointer to an another node of H_{APEX} in the *next* field or a pointer to the node of G_{APEX} in the *xnode* field, but the entry may not have non-NULL value for both *next* and *xnode* fields. If the entry of a node n in H_{APEX} has a pointer to another node m of H_{APEX}, there exists a longer frequently used path represented in m whose suffix is represented by the entry in the node n of H_{APEX}. For example, consider the example of APEX in Figure 11-(b). The *next* field of the entry for the label D in H_{APEX} points to a node that has two entries;

```
Procedure updateAPEX(xnode, ΔESet, path)
begin
1.  if (xnode.visited = TRUE) and  (ΔESet = ∅), return
2.  xnode.visited := TRUE
3.  EdgeSet := ∅
4.  if ΔESet = ∅ {
5.     for each e that is an outgoing edge of xnode do {
6.        newpath := concatenate(path, e.label)
7.        xchild := hash(newpath)
8.        if (xchild = NULL) xchild := newXNode()
9.        if (xchild != e.end) {
10.          if (EdgeSet = ∅) {
11.             for each < u, v >  ∈ xnode.extent do
12.                EdgeSet := EdgeSet ∪ {o | o is an outgoing edge from v}
13.          }
14.          subEdgeSet := a set of edges with the label e.label in EdgeSet
15.          ΔEdgeSet := subEdgeset - xchild.extent
16.          xchild.extent := xchild.extent ∪ ΔEdgeSet
17.          make_edge(xnode, xchild,e.label);
18.          hash.append(newpath, xchild);
19.       }
20.       else ΔEdgeSet := ∅
21.       updateAPEX(xchild, ΔEdgeSet, newpath);
22.    }
23. } else {
24.    for each < u, v >  ∈  ΔESet do
25.       EdgeSet := EdgeSet ∪ {o | o is an outgoing edge fromv}
26.    for each unique label l in EdgeSet do {
27.       newpath := concatenate(path, e.label)
28.       xchild := hash(newpath)
29.       if (xchild = NULL) xchild := newXNode()
30.       subEdgeSet := set of edges labeled l in EdgeSet
31.       ΔEdgeSet := subEdgeset - xchild.extent
32.       xchild.extent := xchild.extent ∪ ΔEdgeSet
33.       make_edge(xnode, xchild, l)
34.       hash.append(newpath, xchild)
35.       updateAPEX(xchild, ΔEdgeSet, newpath);
36.    }
37. }
end
```

Figure 9: An algorithm to update APEX

one is for the path $A.D$ and the other one is for the rest of paths ending with D except $A.D$. Recall that the paths are represented in H_{APEX} in reverse order. If the *xnode* field in the entry of a node n in H_{APEX} points to a node g in G_{APEX}, the extent of g has edges with incoming label path represented by the entry in n.

The basic idea of update is to traverse the nodes in G_{APEX} and update not only the structure of G_{APEX} with frequently used paths but also the *xnode* field of entries in H_{APEX}. While visiting a node in G_{APEX}, we look for the entry of the maximum suffix path in H_{APEX} from the root to the currently visiting node in G_{APEX}. Note that an entry for the maximum suffix path always exists in H_{APEX} since the last label of the path to look for in H_{APEX} always exists by the definition of the required path (See Definition 6).

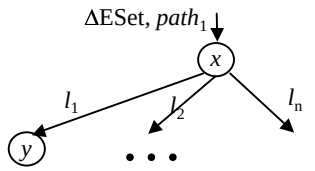
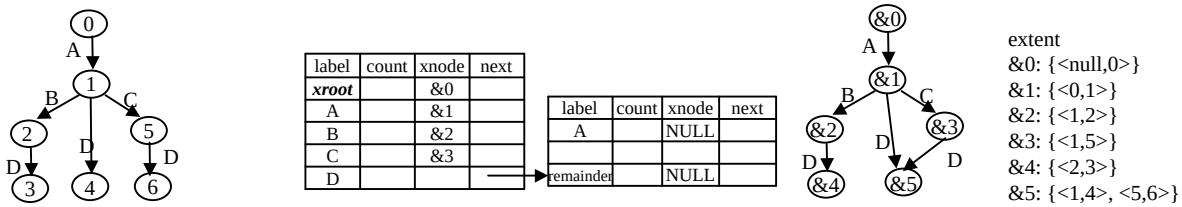


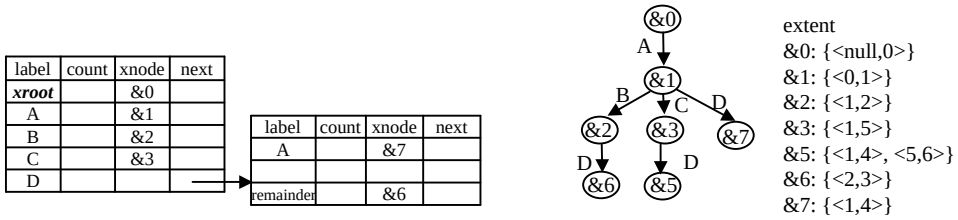
Figure 10: Visiting a node by updateAPEX

Now, we present the *updateAPEX* in Figure 9 that does the modification of APEX with frequently used paths stored in H_{APEX}. Before calling the *updateAPEX*, we first initializes *visited flags* of all nodes in G_{APEX} to FALSE. The *updateAPEX* is executed with the root node in G_{APEX} by calling *updateAPEX*(*xroot*, ∅, NULL) where *xroot* is the root node of G_{APEX}.

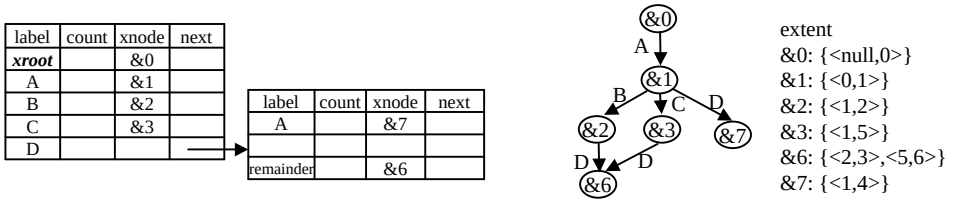
Suppose that we visit a node x in G_{APEX} with a label path $path_1$ and a edge set ΔESet as illustrated in Figure 10. ΔESet is a newly added edges to the extent of x just before visiting the current node. If x was previously visited and ΔESet is empty, then we do nothing since all edges and their subgraphs of x were traversed before (Line (1)). If x is newly visited and ΔESet is empty, we should traverse all outgoing edges of x in G_{xml} to verify the all subnodes of x according to H_{APEX}. For each ending vertex (i.e. e.end) in the outgoing edges of the visiting node in G_{APEX}, we get the pointer *xchild* that represent a node in G_{APEX} with the maximal suffix stored in H_{APEX} of the label path to the visiting node from the root by calling *hash* function (Line (6)-(7)). If the value of *xchild* is NULL, it means that the valid node in G_{APEX} does not exist. Thus, we allocate a new node of G_{APEX} and set to *xchild* (Line (8)). If *xchild* is not NULL, the entry in H_{APEX} points to node in G_{APEX}



(a) G_{XML} (b) before Update



(c) snapshot of updating



(d) after Update

Figure 11: An example for updateAPEX

for a given label path. Thus, we insert the edge set to the extent of *xchild*.

If *xchild* and e.end are different, we compute edge set which should be added to *xchild* (Line (10)-(14)). We insert the newly added edges in the extent of *xchild* to ΔEdgeSet and update the extent of *xchild* (Line (15)-(16)). We next make edge by invoking *make_edge* from this *xnode* to *xchild* with label e.label, if the edge does not exist, and set *xchild* to H_{APEX} with the given label path by calling *make_edge* (Line (17)-(18)). If *xnode* has an outgoing edge to a node in G_{APEX} which is different from *xchild* with label *e.label*, *make_edge* removes this edge. If *xchild* and e.end are equal, there is no change of the extent of the node *xchild* (Line (20)). Thus, ΔESet is set to empty set. Now, we call *updateAPEX* recursively for the child node *xchild*.

Whether a *xnode* is previously visited or not, if there is a change of the extent of it, we should update the subgraph rooted at *xnode* (Line (23)-(37)). In this case, we obtains outgoing edges from the end point of edges in ΔESet (Line (24)-(25)). In order to update the subgraph rooted at *xnode*, we partition the edges based on the labels of edges in ΔESet and update H_{APEX} and G_{APEX} similarly as we processed for the case when ΔESet was empty set. (Line (26)-(36)).

Let us consider the H_{APEX}, G_{APEX} and G_{XML} in Figure 11-(a) and Figure 11-(b). Assume that we invoke *updateAPEX* (*xroot*, $\emptyset$, NULL). Since the ΔESet is empty, the code in Line (4)-(23) in Figure 9 will be executed. Since there is only one outgoing edge with the label A and the ending node &1, we check the entry with H_{APEX} for the path of A. The *xnode* field of the entry returned by *hash* points the node &1. Thus, we do nothing and call *updateAPEX*(&1, $\emptyset$, A) recursively. This recursive call visits the node &1 with label path A. We have three outgoing edges from the node &1. Suppose we consider the node &2 first in the for-loop in line (5). We check the entry in H_{APEX} with the path of $A.B$ and find that the entry points to the node &2. Thus, we do nothing again and invoke *updateAPEX*(&2, $\emptyset$, $A.B$) recursively. Inside of this call, we checks outgoing edges of &2. As illustrated in Figure 11-(b), the end node of an outgoing edge of &2 with label D is &4. However, for the input of $A.B.D$, *hash* returns NULL that is the *xnode* field of the entry for $remainder.D$, which should point to the node in G_{APEX} representing all label paths ending with D except $A.D$. Thus, we make a new node &6 for $remainder.D$, compute extent of &6 and change an outgoing edge of &2 with label D to point out &6. Since there is no outgoing edge, we return back to &1 from recursive call. We next consider the outgoing edge with end node of &5 with label $A.D$ from &1. The H_{APEX} and G_{APEX} including the extents after traversing every node in G_{APEX} with *updateAPEX* are illustrated

in Figure 11-(d).

6. EXPERIMENT RESULTS

We empirically compared the performance of our APEX with the strong DataGuide on real-life and synthetic data sets. In our experiments, we found that APEX shows significantly better performance. In addition, in a number of cases, it is more than an order of magnitude faster than the strong DataGuide. The experiments were performed on Pentium III-866MHz platform with MS-Windows 2000 and 512 MBytes of main memory. The XML4J parser[1] and the XML Generator [2] from IBM was used to parse and to generate XML data. We implemented both the strong DataGuide and APEX in the Java programming language. The data sets were stored on a local disk. We begin by describing the XML data sets and query workload used in the experiment.

Data Sets. The Play is the subset of XML data from the collection of the plays of Shakespeare [9]. Because the Play does not have ID and IDREF typed attributes, it is a tree structured XML data. The FlixML and the GedML are the synthetic data sets from real-life DTDs using the XML Generator from IBM. The Flix Markup Language (FlixML) is a markup language for categorizing B-movie reviews for the XML-based B-movie guides [3]. The GedML is a markup language for the genealogical XML data [9]. These two synthetic data sets are graph structured. The Play data shows a minor irregularity in the structure. The FlixML data has a moderate irregularity and and the GedML data's structure is highly irregular. The other characteristics of the three data sets used in the experiment are summarized in Table 6. The two numbers in the last column of the table represent the number of distinct labels and IDREF typed labels (inside of parentheses), respectively.

Data Set	nodes	edges	lables
Play	48818	48817	21(0)
FlixML	41691	41723	64(3)
GedML	30875	36228	77(14)

Table 1: XML Data Set

Query Workload. To estimate the efficiency of APEX for the query processing, we generated 5000 XML queries randomly. A simple path expression is a sequence of labels starting from the root of the XML data. It is possible that there exists a dereference operator (=>) with an attribute in the simple path expression due to the IDREF type attribute in XML data. In order to generate XML queries, we stored all possible simple path expressions in XML data. To generate a query, we randomly selected a simple path expression, selected a subsequence of the simple expression randomly, and then put the self-or-descendent axis in front of the subsequence. We repeated this process until 5000 queries are generated. We also made sure that the results of the queries are not empty. The queries generated can be think of as XQuery queries [4] having formats of either $//l_1/l_2/\ldots/l_m$ or $//l_1/\ldots/l_i => l_{i+1}/\ldots/l_m$ where l_i is a tag or an attribute (with the prefix of '@'). We randomly selected 20% of the 5000 queries as the query workload. We found that the percentage of simple path expressions in the query workload generated by the above methods was about 25%. We will represent the type of these queries as $QTYPE1$.

To evaluate more complicated partial matching queries, we also generated 500 XML queries having formats of $//l_i//l_j$ on each data set. To make this kind query, we randomly selected a simple path expression and choose two distinct label from the simple path. We will represent the type of these queries as $QTYPE2$.

[1]available at http://www.alpahworks.ibm/tech/xml4j.
[2]available at http://www.alpahworks.ibm/tech/xmlgenerator.
[3]available on http://www.xml.com

6.1 Performance Result

In order to get the feeling about the structures generated by the strong DataGuide and APEX, we presented the statistics regarding indexes in Table 2. For APEX, we varied the `minSup` between 0.002 and 0.05. Typically, the strong DataGuide produces more complex structures than APEX variants. It is not surprising since the strong DataGuide keeps all the possible paths from the root of XML data. Particularly, the size of the strong DataGuide for the highly irregularly structured data (GedML) becomes very large.

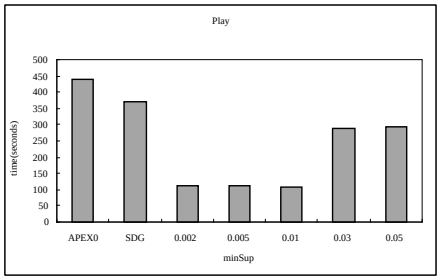
As expected from the definition of APEX^0, it has the most compact structure and size. When we increase the value of `minSup`, the number of frequently used paths decreases. In the query workload we generated, when the value of `minSup` is at least 0.05, the length of every required path become almost one. Thus, the structure of APEX becomes very close to the APEX^0.

minSup	Play		FlixML		GedML	
	Nodes	Edges	Nodes	Edges	Nodes	Edges
SDG	43	42	139	138	13392	16105
APEX^0	22	36	65	117	78	221
0.002	43	42	137	138	1500	6193
0.005	43	42	119	137	652	3007
0.01	43	42	84	132	363	1648
0.03	25	42	67	131	182	793
0.05	23	38	66	121	118	468

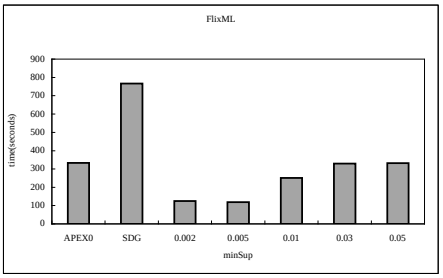
Table 2: Statistics of Index Structures.

We also plotted the total query processing cost with the queries type of $QTYPE1$ for the three data sets using the strong DataGuide and APEX as `minSup` varied from 0.002 to 0.05 in Figure 12. We also showed the cost for APEX^0 because it represents the upper bound of the cost as we increase `minSup`. Note that the required path set becomes a set of paths with the length of one when we increase the `minSup` to high values. Obviously, the query processing cost using APEX^0 should be most slow among APEX variants since we need to perform joins of extents for the path expression of the queries with the size of at least two. Therefore, the query processing pays severe performance penalty and it was illustrated by the graphs for all experimental results.

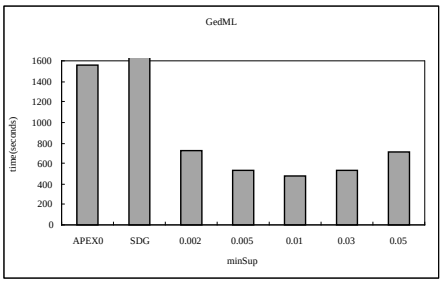
Note that the query processing of the strong DataGuide is more inefficient than APEX^0 for moderate or high irregular



(a) Play



(b) FlixML



(c) GedML

Figure 12: Execution times

structure (FlixML and GedML). The query processing time of APEX^0 for the GedML is about 1500 seconds and that of the strong DataGuide is about 27000 seconds. The inefficiency of strong DataGuides comes from the fact that its size generated for the XML documents with a complex structure becomes very large. As the Table 2 illustrates, the number of nodes and the number of edges in the strong DataGuide generated for the GedML data are 13392 and 16105 respectively, while they are 78 and 221 in APEX^0 produced. Furthermore, to compute a partial matching path query, the query processor should traverse a lot of nodes in the strong DataGuide. While, in APEX, the some queries such as the queries whose length are one can be directly obtained by look-up of H_{APEX}. This result confirms that the strong DataGuide is generally inefficient for complex XML data.

The performance of APEX depends on the value of `minSup`. As `minSup` decreases, the number of frequently used paths increases and more entries is stored in the H_{APEX}. Thus, more queries can be directly obtained by look-up of H_{APEX}.

Even though the sizes of the graph structures of the strong DataGuide and APEX are similar for the data sets with moderate or less irregular structure (Play data and FlixML data) given the `minSup` of 0.002 and 0.005 as shown in Table 2, the query processing cost of APEX is cheaper than that of the strong DataGuide. This is because query results can be directly obtained by the lookup of the hash tree, H_{APEX}, of APEX without traversing the graph structure, G_{APEX}. APEX is significantly better for the highly irregularly structured XML data (GedML) than strong DataGuide. From the result, we can conclude that APEX shows much better performance as the structure of the XML data gets more complex. As we also explained previously, as the value of `minSup` increases, the number of frequent paths decreases and it results in APEX that is very close to APEX^0. Thus, the query processing cost suffers.

To evaluate $QTYPE2$ queries, the query pruning and rewriting technique [11] is applied. To perform query pruning and rewriting, the query processor with strong DataGuide generally traverse the whole index structure several times. However, the query processor with APEX traverses the partial index structure of G_{APEX} with the label l_i. This results that the query pruning and rewriting overhead with APEX is less than that of the strong DataGuide. Even though there is query processing overhead to obtain the query result, APEX shows the best performance over the various data sets. Due to the space limitation, we omit the graph of query performance for $QTYPE2$.

The effectiveness of APEX is determined by `minSup`. In our experiment, APEX was efficient with the value of `minSup` ranging between 0.002 and 0.01. When `minSup` is 0.005, APEX shows the best performance with the query workload we generated over the various XML data.

7. CONCLUSION

In this paper, we propose APEX which is an Adaptive Path indEx for XML data. APEX does not keep all paths starting from the root and utilizes frequently used paths to improve the query performance. In contrast to the traditional indexes such as DataGuides, 1-indexes and the Index Fabric, it is constructed by utilizing the data mining algorithm to summarize paths that appear frequently in query workload. APEX can be incrementally updated in order to minimize the overhead of construction whenever the query workload changes. APEX also guarantees all paths of length two so that any label path expression can be evaluated by joins of extents in APEX without scanning original data.

To support efficient query processing, APEX consists of two structures: the graph structure G_{APEX} and the hash tree H_{APEX}. G_{APEX} represents the structural summary of XML data with extents. H_{APEX} keeps the information for frequently used paths and their corresponding nodes in G_{APEX}. Given a query, we use H_{APEX} to locate the nodes of G_{APEX} that have extents required to evaluate the query.

We implemented our APEX and conducted an extensive experimental study with both real-life and synthetic data sets. Experimental results show that APEX improves query processing cost typically 2 to 54 times better than the traditional indexes, with the performance gap increasing with irregularity of XML data.

8. ACKNOWLEDGMENTS

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